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Energy Performance Anlaysis of Transparent Wood Composite-Based Glazing Systems in Commerical Buildings

Joseph Hoberg Arehart
University of Colorado at Boulder, arehart.jay@gmail.com

ENERGY PERFORMANCE ANLAYSIS OF TRANSPARENT WOOD COMPOSITE-BASED GLAZING SYSTEMS IN COMMERICAL BUILDINGS

by:

JOSEPH HOBERG AREHART

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Prof. Wil V. Srubar III

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Prof. Gregor Henze

____
Prof. John Zhai

Date______________

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline

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Energy Performance Analysis of Transparent Wood Composite-Based Glazing Systems in Commercial Buildings
Thesis directed by Assistant Professor Wil V. Srubar III

Transparent wood composites (TWCs) have 15% the thermal conductivity of silicon-based glass and can be used in alternative glazing systems. Single-paned and double-paned TWC based window assemblies were developed for implementation in commercial reference buildings of three vintages (Pre-1980, Post-1980, and Post-2004) located in 15 climate zones. Energy simulations were performed for baseline buildings and compared against buildings with TWC based glazing systems in place of traditional glass based glazing. In addition, a cost analysis was performed for lab-scale production of TWCs. Results showed that buildings with TWC based windows reduced space conditioning by up to 33.3%. Commercial buildings with high window to wall ratios saw the largest energy savings. Climate zones that are moderate and do not have high annual solar radiation tended to also spend less energy on space conditioning. Yet, some building types such as hotels saw increases in space conditioning energy needs as a result of TWC based window implementations.

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CHAPTER 1 INTRODUCTION

1.1. ENERGY USE IN BUILDINGS

The built environment, particularly in the United States, is a major consumer of energy. In 2010, the United States consumed 97.8 quads of energy, which was representative of 18% of the world's energy consumption. Within the United States, 41% of the energy is consumed by buildings [1]. Figure 1 and Figure 2 show the energy used by buildings in the context of global energy consumption. 77% of global energy use comes from fossil fuels whose carbon emissions are responsible for increased atmospheric carbon-dioxide levels [1,2].

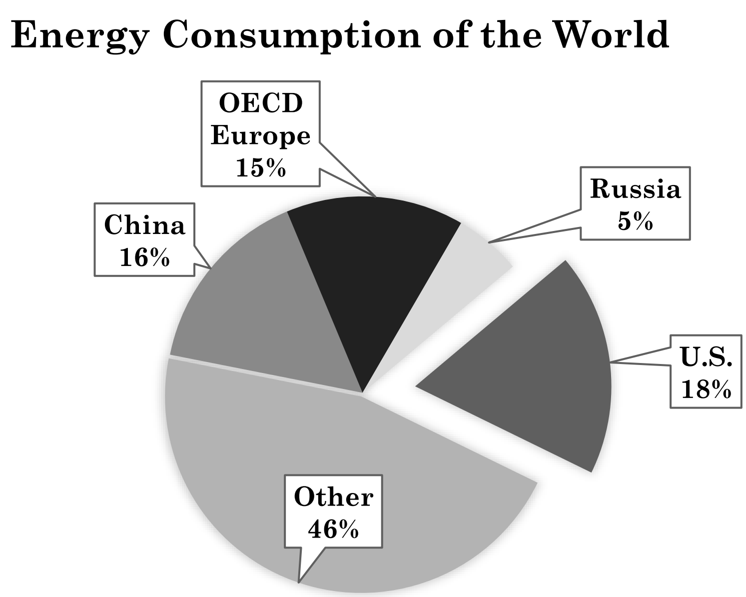

Figure 1. The energy consumption breakdown of the U.S. in the perspective of the world.

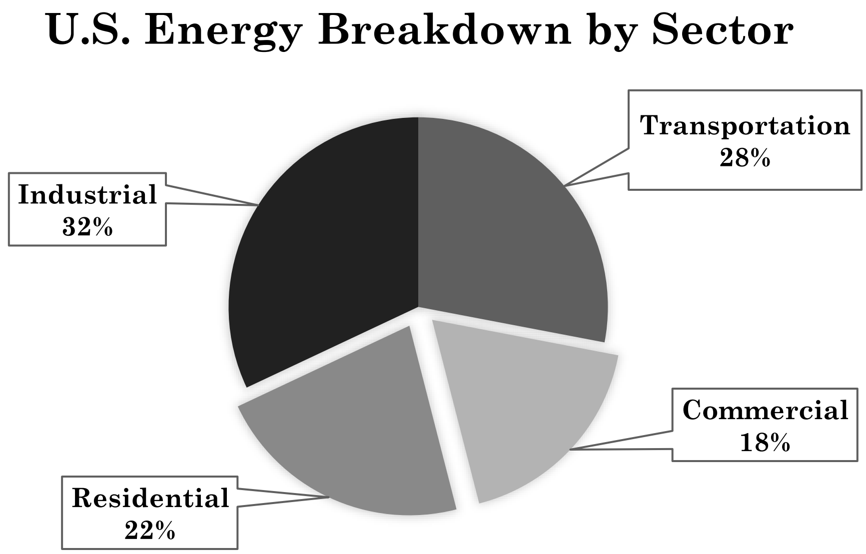

Figure 2. U.S. energy consumption by sector. Buildings represent 40% of the total energy consumption.

The energy consumed by the building sector can be broken into two categories, embodied and operational. In conventional buildings, operational energy can account for 75% of the energy consumed, while even in the most state-of-the-art buildings, operational energy makes up about 50% of the energy consumed [3]. Reductions made in both of these categories can have a significant impact on the total energy consumed by a building.

Operational energy is attributable to a variety of consumption types. Figure 3 shows the typical breakdown. The categories of space heating, lighting and cooling account for 52.7% of the average total energy used by buildings across the U.S., so any reductions to these categories has a major impact on the total energy consumption [1].

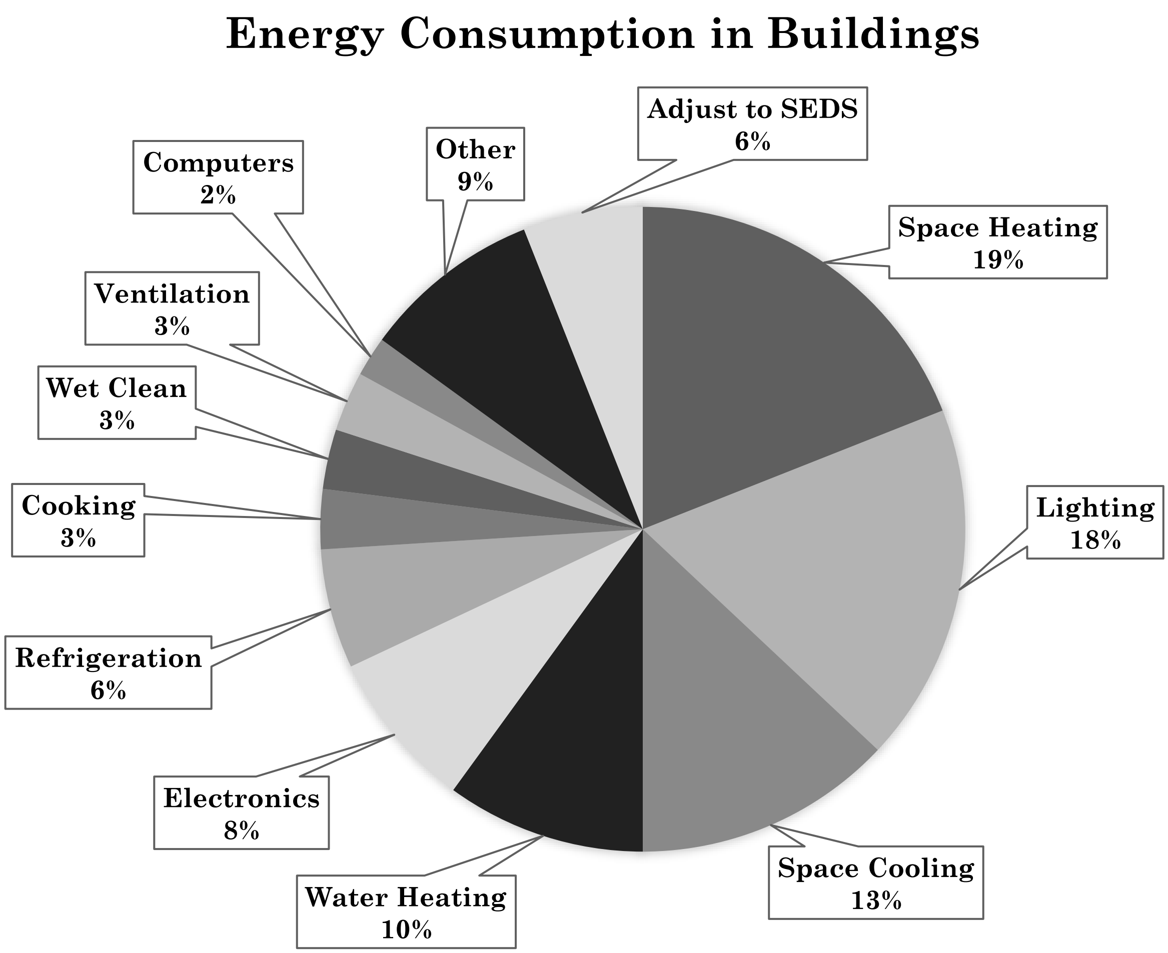

Figure 3. The average energy consumption breakdown within a U.S. building.

1.2. TRADITIONAL GLAZING SYSTEMS

Depending on the climate and building type, fenestrations such as windows play a large role in both heating and cooling loads. As key architectural elements, glazing systems are commonplace in commercial buildings. Much research has gone into understanding how glazing systems affect building performance from both a daylighting and an energy use perspective [4]. Traditional glazing systems have evolved from single-paned windows framed by wood to gas-filled, multi-pane windows with thermally broken window frames. In design, the solar heat gain coefficient (SHGC) and U-values, are chosen by designers to balance the energy spent on heating and cooling. SHGC is a metric to describe the percentage of solar radiation that passes through a window, while U-values are a measure of thermal transmittance. Glazing systems have evolved to have a wide range of these properties so that designers can better control the response of a building to the outdoor temperature and solar heat gains.

1.3. ALTERNATIVE GLAZING SYSTEMS

Innovations in material science has allowed for new glazing systems to be used in the building industry. Alternative glazing systems, such as aerogels and phase change materials, offer dynamic window glazing solutions which are higher performing than their static counterparts [4]. Various types of transparent insulation materials have become an interest to the window manufacturing industry. Glass or plastic-based capillary structures are configured between two pieces of glass, which act as the structure of the assembly. While having insulating properties similar to wall assemblies, transparent insulation materials are typically diffuse and do not provide views which are important architectural features of any building. One emerging class of materials that can maintain views to the exterior in addition to being insulating is transparent wood composites.

1.4. TRANSPARENT WOOD COMPOSITES

Wood is a sustainable material derived from trees and has been used as a fuel source and building material for many centuries. Research has shown that materials derived from wood can be used in bioengineering applications and electronics [5]. As a natural composite material, wood is composed of three polymers: cellulose, hemicellulose, and lignin. These polymers and the way they interact with one another can be manipulated to create new and innovative wood-based materials. One category of wood-based material that is of interest for application in the built environment, due to its optical and thermal properties, is transparent wood composites (TWCs).

Cellulose and hemicellulose are naturally transparent polymers, while lignin is responsible for wood's distinctive color. Thus, the type and quantity of lignin determines wood's optical properties. Various processes exist to delignify wood [5,6]. The fundamentals behind delignification are as follows: wood specimens are soaked in warm (80°C-100°C) solutions containing sodium hydroxide and sodium sulfite for 3-12 hours. Through the soaking process, the lignin is separated from the cellulose and hemicellulose matrix. The specimen is then cleaned and the solvents are exchanged using ethanol and acetone. At this point, the wood is colorless (white) and the resin infiltration process is initiated.

A refractive index-matching polymer, such as poly(methyl methacrylate) (PMMA) is a common resin used in the fabrication of TWCs. The colorless wood specimen is immersed in the resin under high temperatures and a vacuum for 12 hours. Under such temperature and pressure, the resin is drawn into the wood specimen, filling the space previously occupied by the lignin and the open wood cellular structure. Figure 4 shows the final transparent nature of the wood composites (samples are courtesy of Kyle Foster from the University of Colorado Boulder).

Figure 4. Transparent wood composite sample created by Kyle Foster.

TWCs exhibit many of the same properties as original wood samples, yet their optical properties are visibly altered. Visible transmittance is as high as 90% across the visible spectrum (400nm – 800nm), although high transmittance haze is observed [5–8]. TWCs also maintain the thermal properties of wood, resulting in a thermal conductivity of 0.15 W/m/K in the cross-plane direction. Figure 5 shows a comparison of the thermal conductivity between silicon-based glass and TWCs [6]. Note that in its radial direction, TWCs show an 85% reduction in thermal conductivity. Coupling the optical and thermal properties of TWC results in an innovative material that is a potential candidate for glazing materials in buildings.

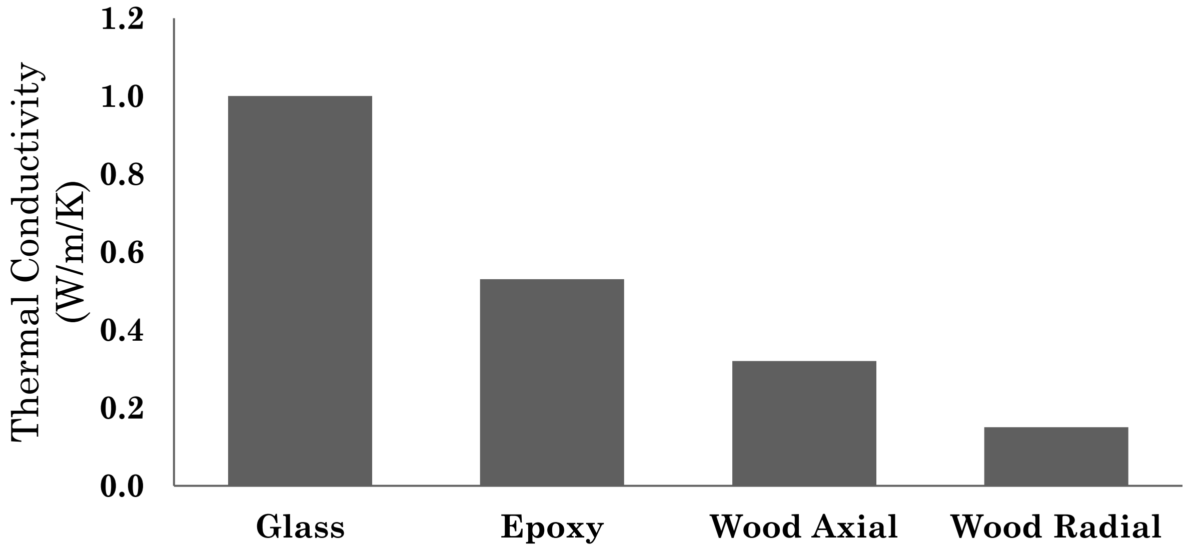

Figure 5. Comparison of thermal conductivities between glass and transparent wood composites. Note that in the wood's radial direction, there is an 85% decrease in the thermal conductivity.

1.5. SCOPE OF WORK

The purpose of this thesis seeks to quantify, for the first time, the energy savings potential of using transparent wood composites as an alternative glazing system in commercial buildings across the United States. Two models for TWC window assemblies, a single-paned and a double-paned window, are derived and implemented in commercial reference buildings. Energy simulations for each commercial building type are investigated to determine in what locations and building types TWC based window assemblies can yield energy savings. Furthermore, this investigation can be used to inform further material science and design as TWC based windows become a more viable technology.

CHAPTER 2 MODEL AND SIMULATION ENVIRONMENT

2.1. WINDOW MODULE

Two windows assemblies were developed for implementation in an energy simulation environment - a single-paned window and a double-paned window. These systems were created using the WINDOW 7.4 algorithm developed by Lawrence Berkeley National Laboratory (LBNL) [9]. Each glazing system is comprised of glass and gap materials, which are combined to create innovative glazing systems. A window module is then formed by combining the glazing system with a window frame. Each window assembly is described by a U-value, solar heat gain coefficient (SHGC), and visible transmittance (VT). The following sections describe the properties and calculations used to create the both the single-paned and double-paned windows assemblies.

2.1.1. PROPERTIES OF WINDOW PANES AND GAPS

To be used by the WINDOW 7.4 algorithm, each material of the window assembly is assigned properties. Each glass material is comprised of a thickness, solar transmittance, solar reflectance, visible transmittance, visible reflectance, infrared transmittance, emissivity, and thermal conductivity. Properties for each face of the glass is defined by the variables described in Table 1 [9].

Table 1. Variables used in the WINDOW7.4 algorithm.

Variable	Description	Units
Thickness	Glass thickness	mm
Tsol	Solar transmittance of the glazing layer	--
Rsol1	Solar reflectance of the glazing layer, exterior-facing side	--
Rsol2	Solar reflectance of the glazing layer, interior-facing side	--
Tvis	Visible transmittance of the glazing layer	--
Rvis1	Visible reflectance of the glazing layer, exterior-facing side	--
Rvis2	Visible reflectance of the glazing layer, interior-facing side	--
Tir	Thermal infrared (longwave) transmittance of the glazing layer	--
emis1	Infrared (longwave) emittance of the glazing layer, exterior-facing side	--
emis2	Infrared (longwave) emittance of the glazing layer, interior-facing side	--
Cond	Thermal conductivity	W/m/K

Table 2 describes the properties of both traditional silicon-based glazing, and that of TWCs. Silicon-based glass properties are taken from the LBNL glass library (*ID102: CLEAR_3.DAT*). When available, properties were derived from TWC samples. Otherwise, the properties of PMMA were used (specifically for the solar transmittance, solar reflectance, and emissivity).

In double-paned windows, air or other gasses occupy the space between panes to provide additional thermal resistance. Table 3 summarizes the properties of air used in the gap to be used in the TWC based window assemblies. These properties are taken from the LBNL Gap Library (*ID 1: Air*).

Table 2. A comparison between the properties of traditional glazing and those for TWC.

Property	Silicon-based Glass	Transparent Wood Composite	Source (for TWC)
Thickness (mm)	3.050	14.00	[6]
Tsol	0.834	0.722	[10]
Rsol1	0.075	0.095	[10]
Rsol2	0.075	0.095	[10]
Tvis	0.899	0.900	[7,8]
Rvis1	0.083	0.100	[7,8]
Rvis2	0.083	0.100	[7,8]
Tir	0.000	0.000	--
emis1	0.840	0.850	[11]
emis2	0.840	0.850	[11]
Cond (W/m/K)	1.000	0.150	[6]

Table 3. Summary of the properties of air used in the double-paned window assembly.

Property	Air
Conductivity (W/m/K)	0.0241
Viscosity (kg/m/s)	0.000017
C_p (J/kg/K)	1006.1
Density (kg/m^3)	1.2925
Prandtl Number	0.7197

2.1.2. PROPERTIES OF GLAZING SYSTEM

A glazing system is created by combining the glass panes and, if applicable, the air gap. The properties of the glazing system can be determined through the THERM 2.0 computational method. THERM is a finite element method of analysis, which numerically solves two-dimensional energy equations. Based upon the geometry, boundary conditions, and material properties, a mesh is created.

Numerically solved and post-processed, a U-factor is developed for a glazing assembly based upon the environmental conditions [12]. The method by which the U-value is determined are described by the NFRC (National Fenestration Rating Council) 100-2014 standard, while the SHGC, and VT calculation methods are described in the NRFC 200-2014 standard [13,14]. Table 4 and Table 5 describe the environmental conditions under which the U-factor, SHGC, and VT were determined.

Table 4. Environmental conditions described by NFRC 100-2014 for calculating U-values.

Variable	Value (SI)
Outdoor Temperature	-18°C
Indoor Temperature	21°C
Wind Speed	5.5 m/s
Wind Direction	Windward
Direct Solar	0 W/m^2
Sky Temperature	-18°C
Sky Emissivity	1.00

Table 5. Environmental conditions described by NFRC 200-2014 for calculating SHGC and visible transmittance.

Variable	Value (SI)
Outdoor Temperature	32°C
Indoor Temperature	24°C
Wind Speed	2.75 m/s
Wind Direction	Windward
Direct Solar	783 W/m^2
Sky Temperature	32°C
Sky Emissivity	1.00

Two glazing assemblies were created – a single-paned system and a double-paned system. The single-paned system consists of a single layer of 14mm TWC, while the double-paned system consists of two layers of 14mm TWCs separated by a 12mm air gap. Figure 6 shows a schematic detail of both glazing systems. Typical glass panes need to only by 3-6mm thick to be within deflection limits as a result of wind loading. In contrast, TWCs have a lower stiffness, resulting in an increased required thickness of assembly to meet deflection criteria.

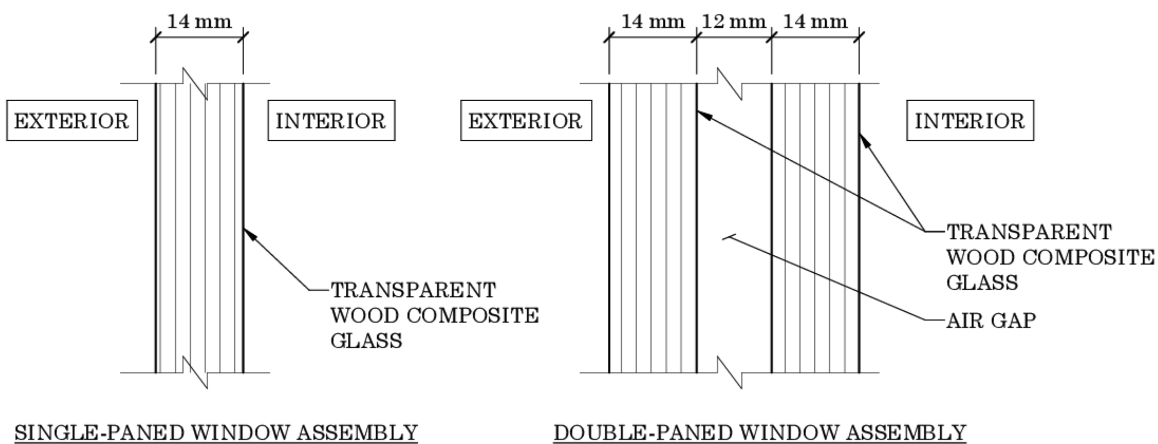

Figure 6. Schematic drawing of single and double paned glazing assemblies.

2.1.3. PROPERTIES OF WINDOW ASSEMBLIES

When glazing systems are combined with window frames, and given dimension, the window assembly's thermal and optical properties can be determined. In the THERM computational method, an area-weighted average of the components is used to determine the properties. Components of both the double-paned and single-paned assemblies are described in Figure 8. Equation 1 describes the area-weighted calculations for the U-value of a window assembly. *U* represents the individual product U-factor (W/m^2/K), while *A* represents the area (m^2). Each subscript represents the components of the window assembly:

$$f = frame; \quad d = divider; \quad e = edge\ of\ glazing;$$
$$c = center\ of\ glazing; \quad de = edge\ of\ divider$$

Similarly, the SGHC and VT are calculated in the same manner by Equation 2 and Equation 3. Table 6 describes the results of each window assembly's property. The single-paned and double-paned assemblies are assumed to be picture windows without any dividers. Figure 7 shows the dimensions of both the window pane area and frame.

$$U_t = \frac{\left[\sum(U_f * A_f) + \sum(U_d * A_d) + \sum(U_e * A_e) + \sum(U_{de} * A_{de}) + \sum(U_c * A_c)\right]}{A_{pf}} \quad \text{Equation 1}$$

$$SHGC_t = \frac{\left[\sum(SHGC_f A_f) + \sum(SHGC_d A_d) + \sum(SHGC_e A_e) + \sum(SHGC_{de} A_{de}) + \sum(SHGC_c A_c)\right]}{A_{pf}} \quad \text{Equation 2}$$

$$VT_t = \frac{\left[\sum(VT_f * A_f) + \sum(VT_d * A_d) + \sum(VT_e * A_e) + \sum(VT_{de} * A_{de}) + \sum(VT_c * A_c)\right]}{A_{pf}} \quad \text{Equation 3}$$

Table 6. Calculated properties for each component of window assembly.

Assembly Component	U-Value (W/m^2/K)	SHGC	VT	Area (m^2)
Aluminum Frame (no break)	3.970	0.00	0.00	0.294
Single-Paned Glazing	3.837	0.799	0.900	1.207
Double-Paned Glazing	1.835	0.668	0.860	1.207

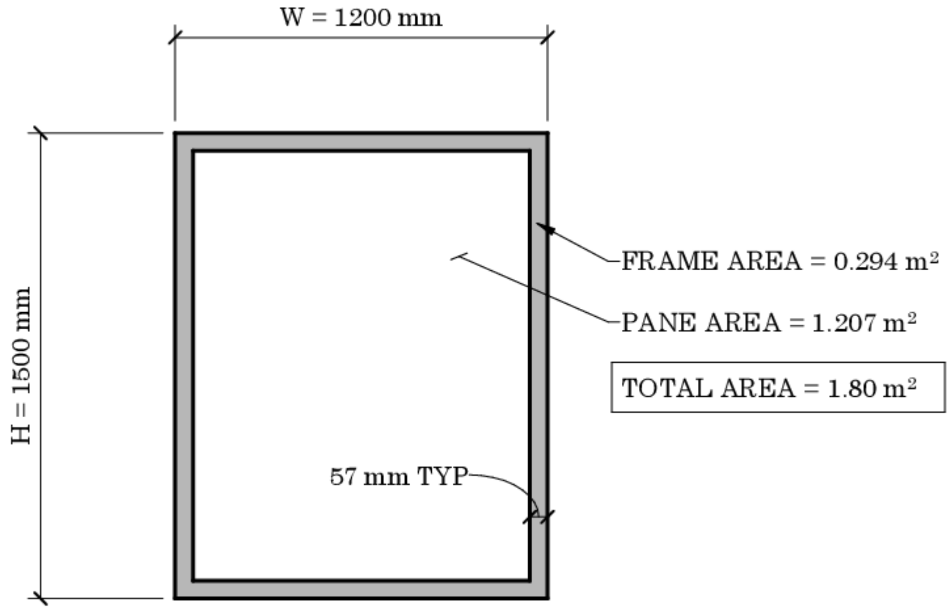

Figure 7. Picture window geometry including frame area and pane area.

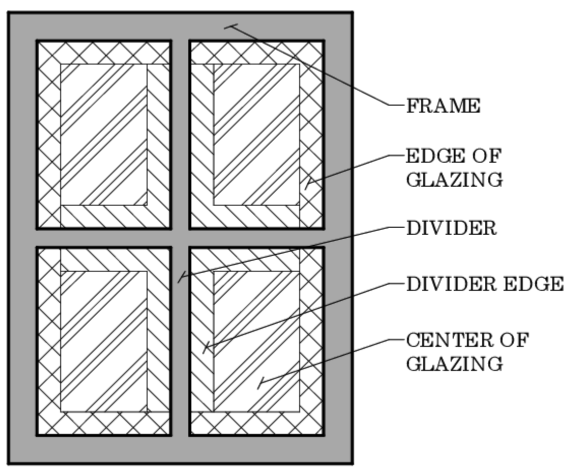

Figure 8. Components of window assembly. The assembly properties are determined based on an area-weighted average of the individual component properties.

2.2. ENERGYPLUS MODULE

2.2.1. SIMPLE WINDOW MODEL

To implement the TWC windows within a whole-building energy simulation tool, the *Simple Window Model* is utilized within EnergyPlus. The Simple Window Model is applicable, due to the scope of this study being to quantify the potential energy savings of TWC window assemblies. A fundamental assumption of the Simple Window Model is that the glazing is specular [15]. While the current TWC that have been produced are not completely specular (have high haze), this study seeks to quantify the energy savings potential of TWC glazing. Current research suggests that TWCs have the potential to be specular, given improved processing, and thus this assumption is considered valid for the scope of this study.

The first step of the *Simple Window Model* is to determine the glass-to-glass resistance by combining the heat transfer between the interior and exterior surfaces of the window as described by Equation 4 [15].

$$R_{l,w} = \frac{1}{U} - R_{i,w} - R_{o,w} \qquad \text{Equation 4}$$

Where:

$R_{i,w}$ = Resistance of interior film coefficient under winter conditions (m^2 K/W)

$R_{o,w}$ = Resistance of exterior film coefficient under winter conditions (m^2 K/W)

$R_{l,w}$ = Bare window resistance with no film coefficient under winter conditions (m^2 K/W)

The next steps involve determining the layer thickness and thermal conductivity, described by Equation 5 and Equation 6 respectively.

$$Thickness = \begin{cases} 0.002 & for\ \frac{1}{R_{l,w}} > 7.0 \\ 0.05914 - \frac{0.00714}{R_{l,w}} & for\ \frac{1}{R_{l,w}} \leq 7.0 \end{cases} \qquad \text{Equation 5}$$

$$\lambda_{eff} = \frac{Thickness}{R_{l,w}} \qquad \text{Equation 6}$$

The solar transmittance is determined by Equation 7 through Equation 10 [16].

$$T_{sol} = 0.939998\, SHGC^2 + 0.20332\, SHGC; \quad U > 4.5; \quad SHGC < 0.7206 \qquad \text{Equation 7}$$

$$T_{sol} = 1.30415\, SHGC - 0.30515; \quad U > 4.5; \quad SHGC \geq 0.7206 \qquad \text{Equation 8}$$

$$T_{sol} = 0.41040\, SHGC; \quad U < 3.4; \quad SHGC \leq 0.15 \qquad \text{Equation 9}$$

$$T_{sol} = 0.085775\, SHGC^2 + 0.963954\, SHGC - 0.084958; U > 3.4; SHGC > 0.15 \qquad \text{Equation 10}$$

While the solar reflectance are correlated by the film conditions of the interior and exterior surfaces [16]. Visible properties of the window assemblies in EnergyPlus are determined by that of 14 mm samples measured in the literature [6]. The results from the Simple Window Model for both the single-paned and double-paned assemblies are summarized in Table 7.

Table 7. Final window assemblies (single-paned and double-paned) properties for implementation into EnergyPlus.

Window Assembly	U ($W/m^2/k$)	U ($Btu/hr/ft^2/°F$)	SHGC	VT
Single-Paned	3.793	0.668	0.696	0.752
Double-Paned	2.329	0.410	0.586	0.719

2.2.2. MODEL IMPLEMENTATION

The OpenStudio (v1.14.0) software was used to implement the EnergyPlus (v8.7.0) simulation program. Various OpenStudio and EnergyPlus measures were utilized in the creation of reference buildings and their modifications. From the building component library, the *Create DOE Prototype Building* measure was implemented to create commercial reference buildings. To modify the reference buildings with TWC based glazing, an OpenStudio measure was written in Ruby.

2.2.3. COMMERCIAL REFERENCE BUILDINGS

In order to determine energy savings a new technology might have in a commercial building, the U.S. Department of Energy (DOE) has created 16 reference buildings in 15 U.S. locations. These 16 building types directly represent over 60% of the commercial building stock, and are close approximations of other building types [17]. For the scope of this study, the number of buildings considered is reduced to 11. Buildings with high internal loads or low window to wall ratios (WWR), including quick and full services restaurants, hospitals, and supermarkets, were omitted. Figure 9 and Table 8 show each climate zone, their geographic location, and representative city [18], while Table 9 shows the building types and their key features.

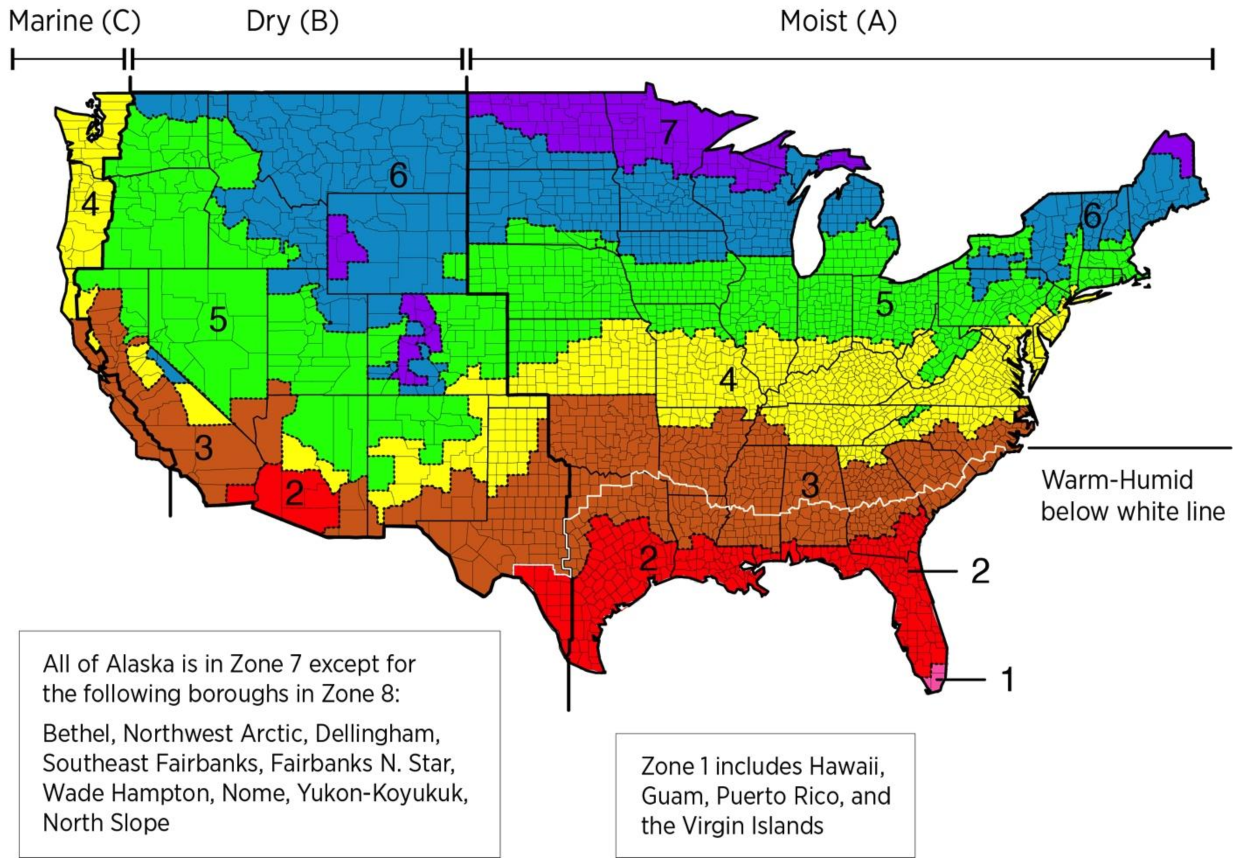

Figure 9. ICC climate zone map [18].

Models have been created for three different eras of construction: new construction, existing buildings constructed in or after 1980 ("Post-1980"), and existing buildings constructed before 1980 ("Pre-1980"). Each model has the same form, floor plan, and operating schedules. The models only differ in their construction type, primarily the insulation values, minimum lighting levels, and efficiencies. For the new construction, the buildings conform to ASHRAE Standard 90.1-2004, while the Post-1980 models meet ASHRAE Standard 90.1-1989. The Pre-1980 models do not conform to any particular standard but are derived from previous studies and standards [17].

Table 8. Climate zone designation, representative city, and weather file locations.

Climate Zone	Representative City	TMY3 Weather File Location
1A	Miami, Florida	Miami, Florida
2A	Houston, Texas	Houston, Texas
2B	Phoenix, Arizona	Phoenix, Arizona
3A	Atlanta, Georgia	Memphis, Tennessee
3B	Las Vegas, Nevada	El Paso, Texas
3C	San Francisco, California	San Francisco, California
4A	Baltimore, Maryland	Baltimore, Maryland
4B	Albuquerque, New Mexico	Albuquerque, New Mexico
4C	Seattle, Washington	Salem, Oregon
5A	Chicago, Illinois	Chicago, Illinois
5B	Denver, Colorado	Boise, Idaho
6A	Minneapolis, Minnesota	Burlington, Vermont
6B	Helena, Montana	Helena, Montana
7A	Duluth, Minnesota	Duluth, Minnesota
8A	Fairbanks, Alaska	Fairbanks, Alaska

Table 9. Summary of important properties of each building considered in the study.

Building Type	Number of Stories	Floor Area (ft2)	Window Area (ft2)	WWR
Large Hotel	6	122,120	13,068	26.63%
Small Hotel	4	43,202	1,983	10.87%
Large Office	12	498,588	49,899	38.05%
Medium Office	3	53,628	7,027	33.01%
Small Office	1	5,502	600	19.81%
Midrise Apartment	4	33,741	3,304	19.90%
Primary School	1	73,959	9,463	35.00%
Secondary School	2	210,887	22,484	35.00%
Retail Stand	1	24,692	903	7.13%
Retail Strip	1	22,500	1,338	10.50%
Warehouse	1	52,045	25,959	0.71%

2.2.4. REPLACEMENT OF GLAZING SYSTEMS

An OpenStudio Measure was written to replace all subsurface properties in the reference buildings with the properties of either single-paned or double-paned TWC windows. Table 10 and Table 11 describe the window properties for the original reference buildings based on climate zone, while Figure 10 and Figure 11 show a comparison of the typical single-paned and double-paned system when compared to TWC window assemblies.

Following the trend of existing reference buildings, single-paned TWC window assemblies were changed in climate zones 1A, 2A, 2B, and 3C. Double-paned TWC assemblies were incorporated into buildings in climate zones 3A, 3B, 4A, 4B, 4C, 5A, 5B, 6A, 6B, 7A, and 8A.

Table 10. Overall U-Value (Btu/hr/ft^2/°F) for reference buildings.

Location	Climate Zone	Pre-1980	Post-1980	Post-2004
Miami, FL	1A	1.22	1.22	1.22
Houston, TX	2A	1.22	1.22	1.22
Phoenix, AZ	2B	1.22	1.22	1.22
Atlanta, GA	3A	1.22	0.72	0.57
Las Vegas, NV	3B	1.22	1.22	0.57
San Francisco, CA	3C	1.22	0.72	1.22
Baltimore, MD	4A	1.22	0.59	0.57
Albuquerque, NM	4B	1.22	0.72	0.57
Seattle, WA	4C	1.22	0.72	0.57
Chicago, IL	5A	0.62	0.59	0.57
Denver, CO	5B	0.62	0.59	0.57
Minneapolis, MN	6A	0.62	0.52	0.57
Helena, MT	6B	0.62	0.52	0.57
Duluth, MN	7	0.62	0.52	0.57
Fairbanks, AK	8	0.62	0.52	0.35

Table 11. Overall Solar Heat Gain Coefficient for reference buildings.

Location	Climate Zone	Pre-1980	Post-1980	Post-2004
Miami, FL	1A	0.54	0.25	0.25
Houston, TX	2A	0.54	0.25	0.25
Phoenix, AZ	2B	0.54	0.25	0.25
Atlanta, GA	3A	0.54	0.25	0.25
Las Vegas, NV	3B	0.54	0.44	0.25
San Francisco, CA	3C	0.54	0.25	0.25
Baltimore, MD	4A	0.54	0.39	0.34
Albuquerque, NM	4B	0.54	0.36	0.39
Seattle, WA	4C	0.54	0.36	0.39
Chicago, IL	5A	0.54	0.39	0.39
Denver, CO	5B	0.41	0.39	0.39
Minneapolis, MN	6A	0.41	0.39	0.39
Helena, MT	6B	0.41	0.39	0.39
Duluth, MN	7	0.41	0.39	0.39
Fairbanks, AK	8	0.41	0.49	0.49

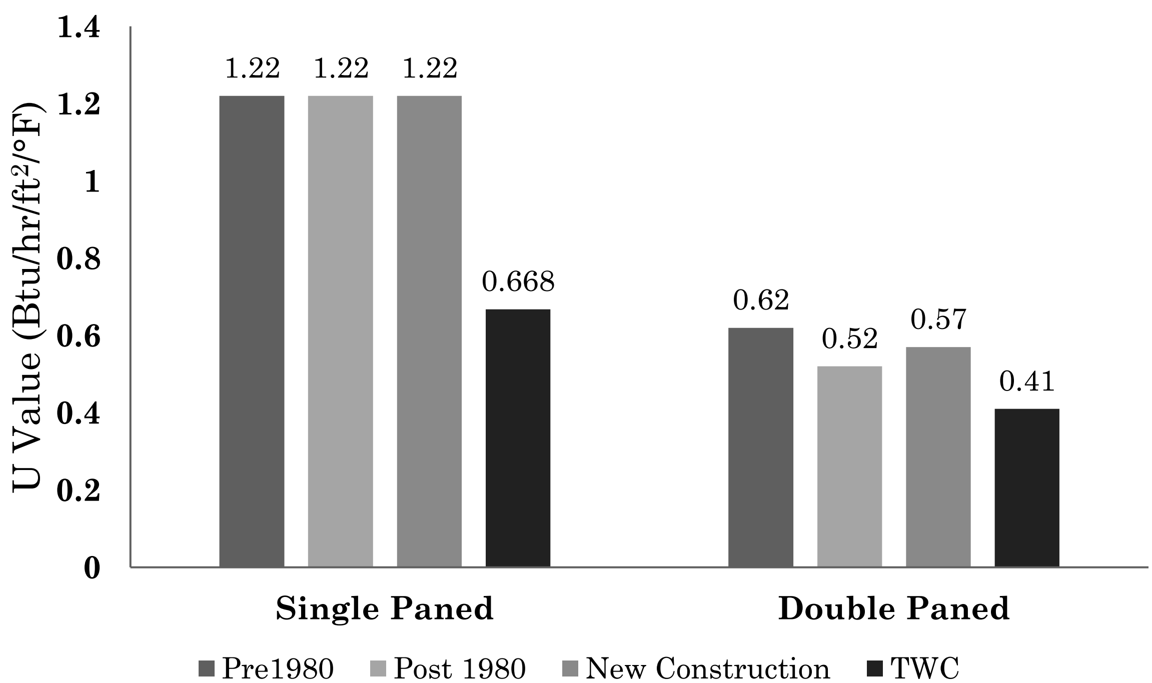

Figure 10. U-value of single-paned and double-paned glazing systems for reference buildings as well as TWC assemblies.

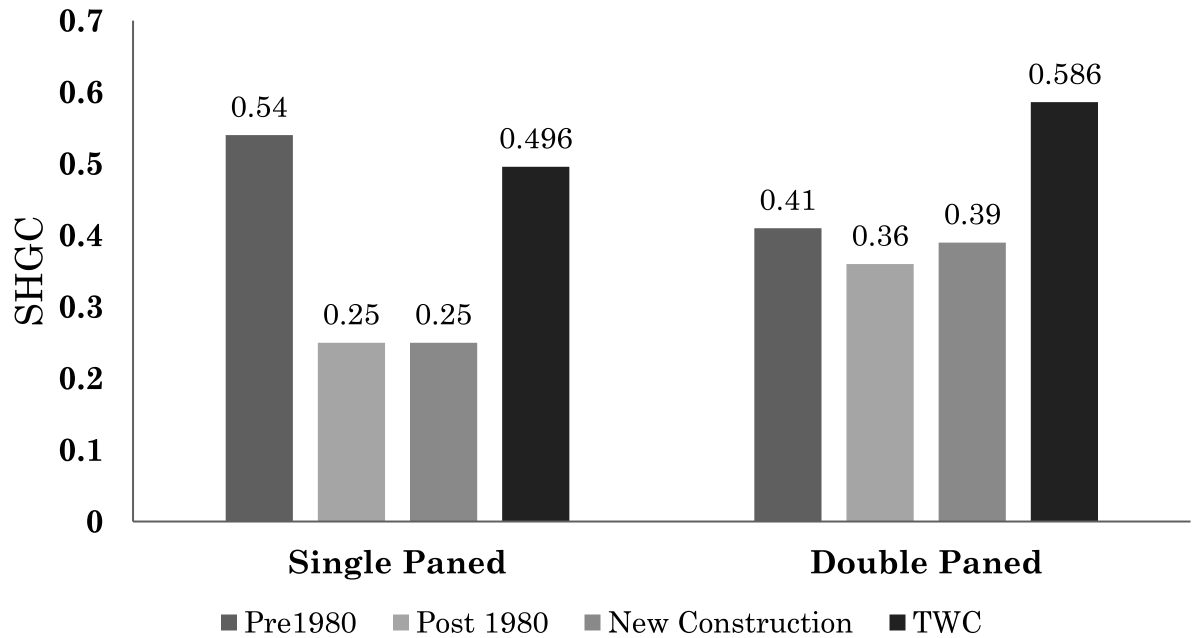

Figure 11. SHGC of single-paned and double-paned glazing systems for reference buildings as well as TWC assemblies.

CHAPTER 3 RESULTS AND DISCUSSION

3.1. EFFECT OF CLIMATE ZONE ON SPACE HEATING AND COOLING

The exterior conditions play an important role in the selection of fenestrations. To understand which climate zones are best suited TWC window assembly retrofits, EnergyPlus simulations were run for each combination of building type and climate zone. The following sections detail the energy savings for each building type compared against its different construction eras (Pre-1980 retrofit, 1980-2004 retrofit, and Post-2004 construction). Figure 12 through Figure 22 describe the energy savings for each building type across all climate zones and building construction vintages.

Buildings with high WWRs, such as the Primary School, Secondary School, Small office, Medium Offices, and Large Offices, saw the most savings in space heating and cooling especially Pre-1980 retrofits in climate zones 3 and 4. A Post-2004 Primary School in climate zone 3C (San Francisco) could see a potential reduction of 20% through the implementation of TWC-based single-paned windows. Meanwhile, a Pre-1980 Large Office building in climate zone 4C sees savings of 33% when retrofitted with double-paned TWC based windows. Climate zones 3 and 4 see less solar radiation than others with similar outdoor temperature profiles, which reduces the impact of the SHGC. The TWC-based assemblies have a higher SHGC than those typical of Post-2004 constructions, which allows for space heating savings in the winter larger than the increases in space cooling during the summer. Section 3.3 provides further discussion on the space heating and cooling tradeoffs typical of the reference buildings.

Climate zone 3C sees the largest fluctuations in energy savings, or lack thereof. The TWC based windows provide larger energy savings compared to other climate zones, which can be explained by the Post-2004 reference buildings reverting back to having single-paned windows as seen in Pre-1980 vintage buildings.

Some of the buildings, including the Large Hotel and Small Hotel, saw negative impacts through the implementation of TWC based windows. The load profiles and operating schedules of these buildings are different from other buildings, which may account for negative impacts of more thermally insulating windows.

The Midrise Apartment shows consistent savings across all climate zones and building vintage. Maximum savings are centralized in climate zones 4A, 4B, and 4C. The consistent space heating and cooling savings suggest that residential buildings may have greater potential for TWC based window retrofits than commercial buildings.

The Warehouse, Standalone Retail, and Stripmall Retail, see little savings to space heating and cooling when TWC based windows are implemented. Due to the low WWR ratio, factors other than solar heat gains and thermal envelope losses contribute to the space conditioning needs.

Building geometry, orientation, WWR, internal loads, and operating schedules contribute to the performance of any building. These reference buildings are representative of the U.S. commercial building stock, but are not intended to represent particular building designs. As such, decreases or increases in space heating and cooling as a result of TWC based window implementation will be dependent on the building program and geometry.

3.1.1. LARGE HOTEL

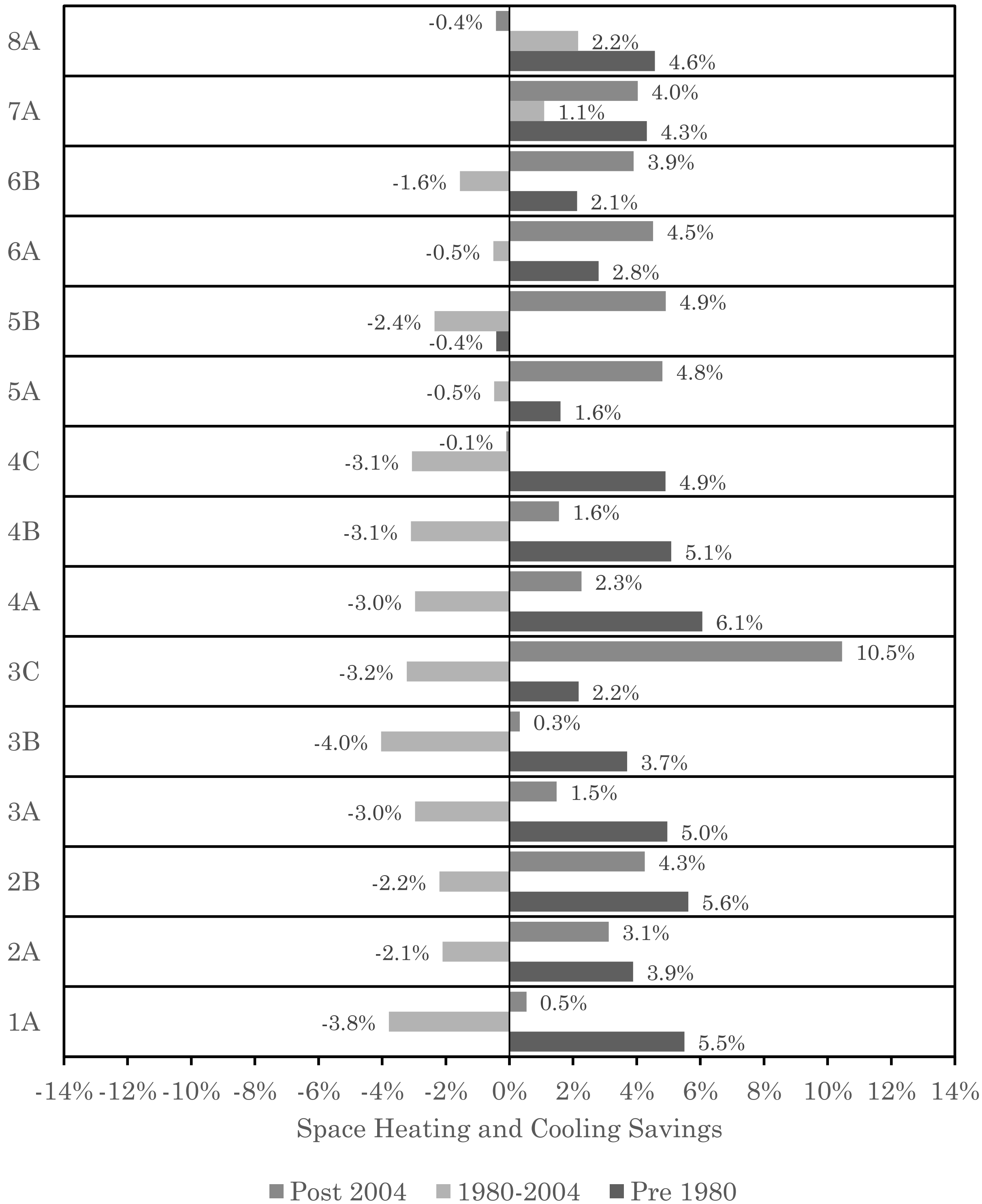

Figure 12. Percent savings of space heating and cooling energy for a Large Hotel for 15 climate zones across all building eras.

3.1.2. SMALL HOTEL

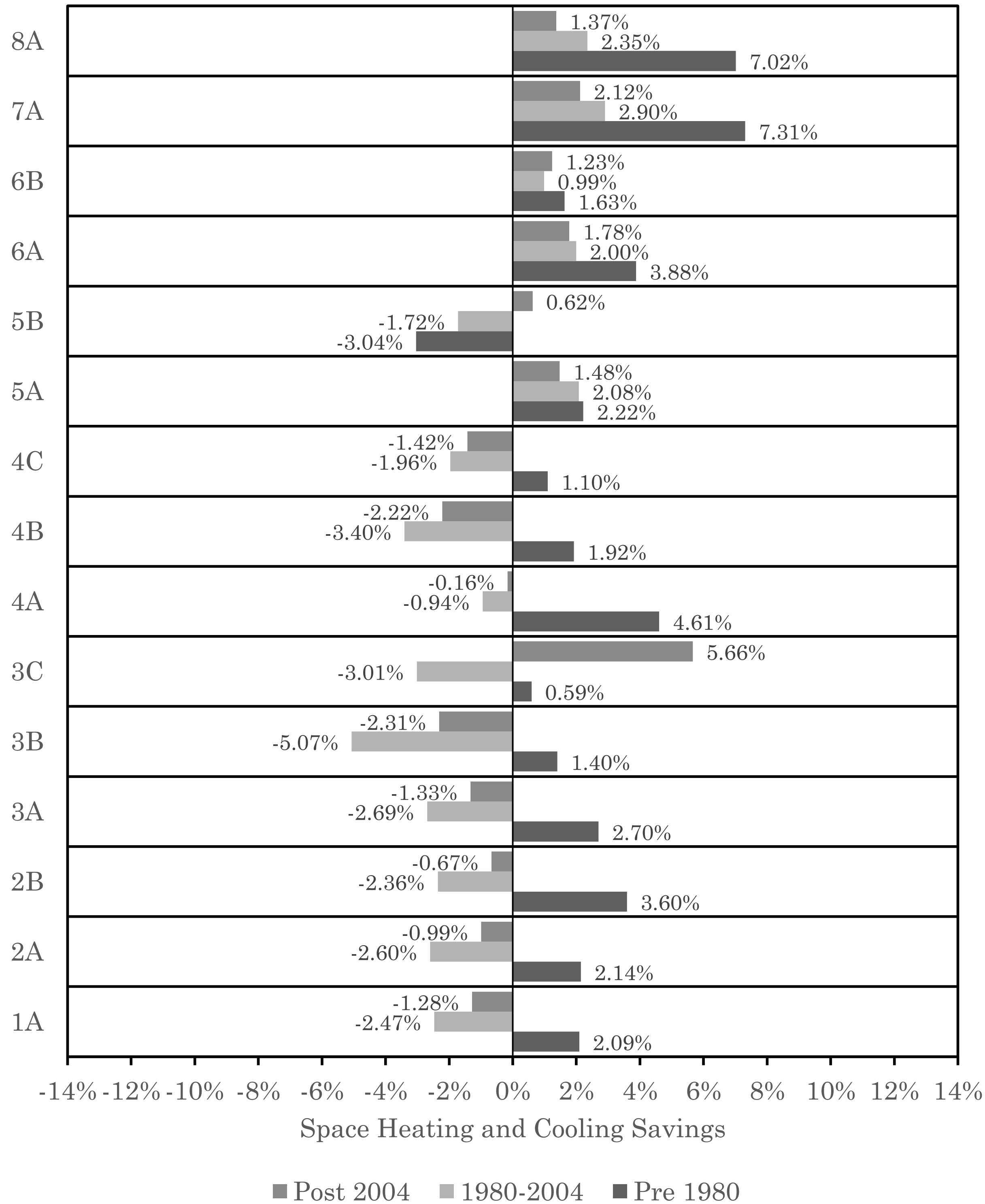

Figure 13. Percent savings of space heating and cooling energy for a Small Hotel for 15 climate zones across all building eras.

3.1.3. LARGE OFFICE

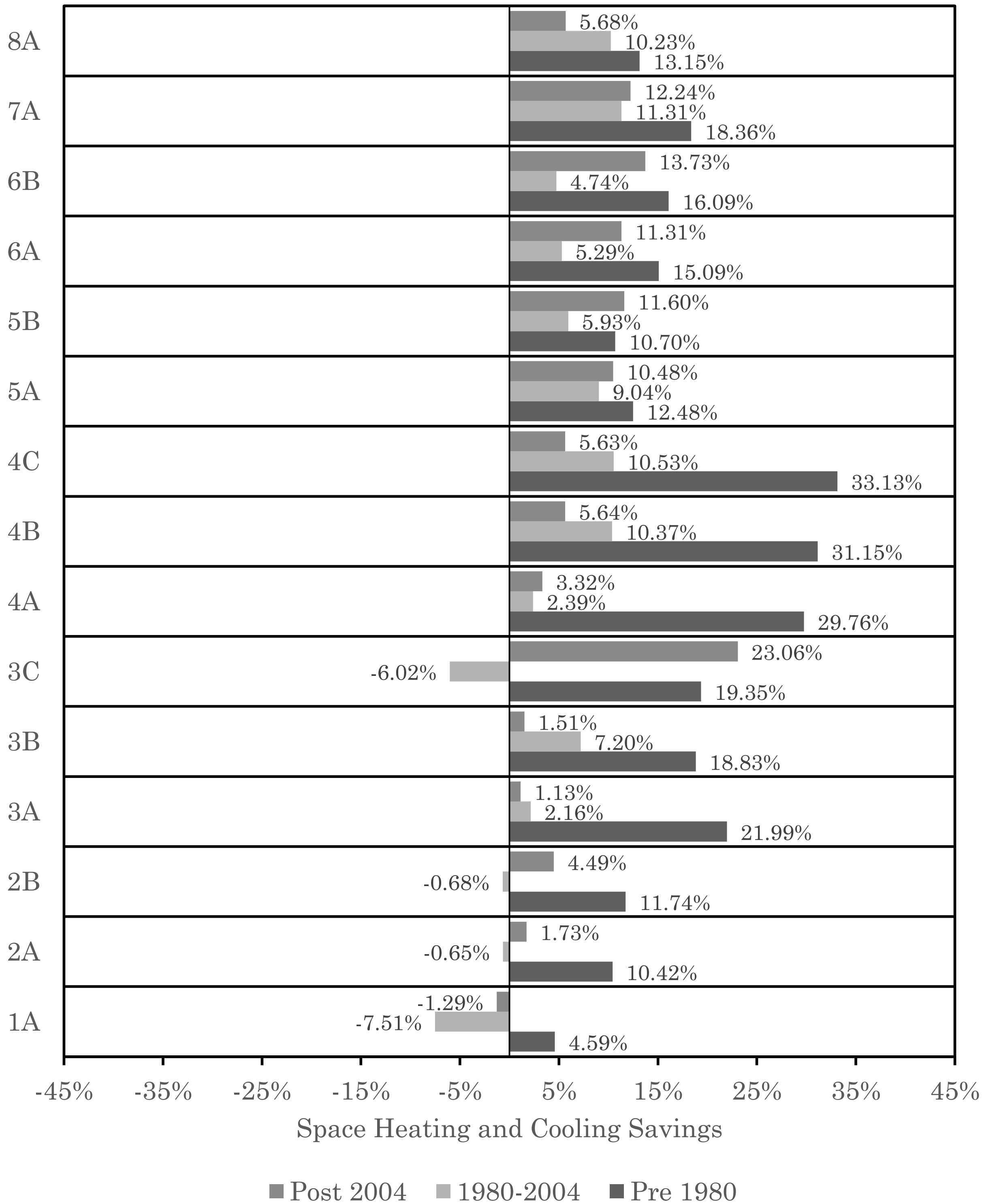

Figure 14. Percent savings of space heating and cooling energy for a Large Office for 15 climate zones across all building eras.

3.1.4. MEDIUM OFFICE

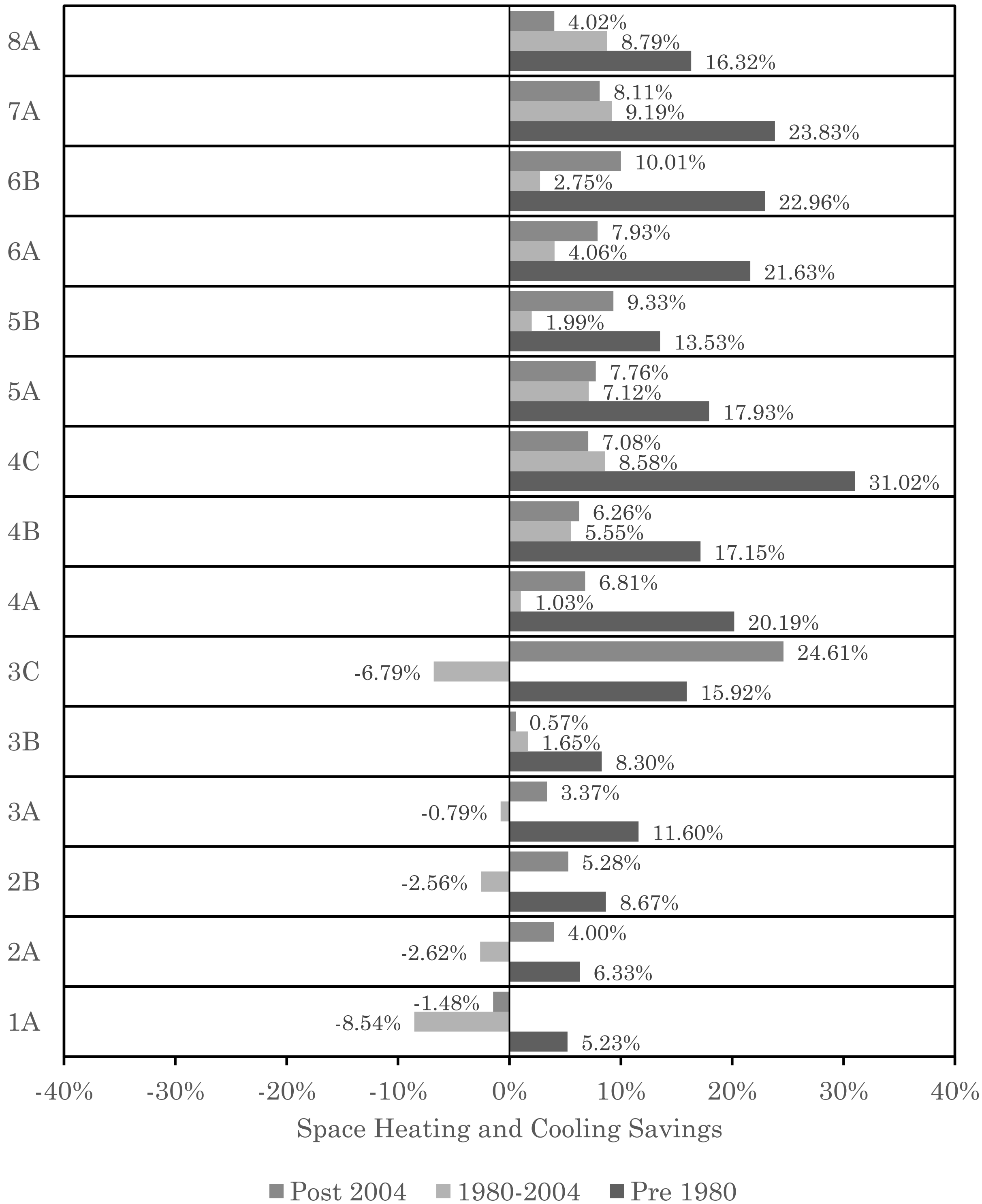

Figure 15. Percent savings of space heating and cooling energy for a Medium Office for 15 climate zones across all building eras.

3.1.5. SMALL OFFICE

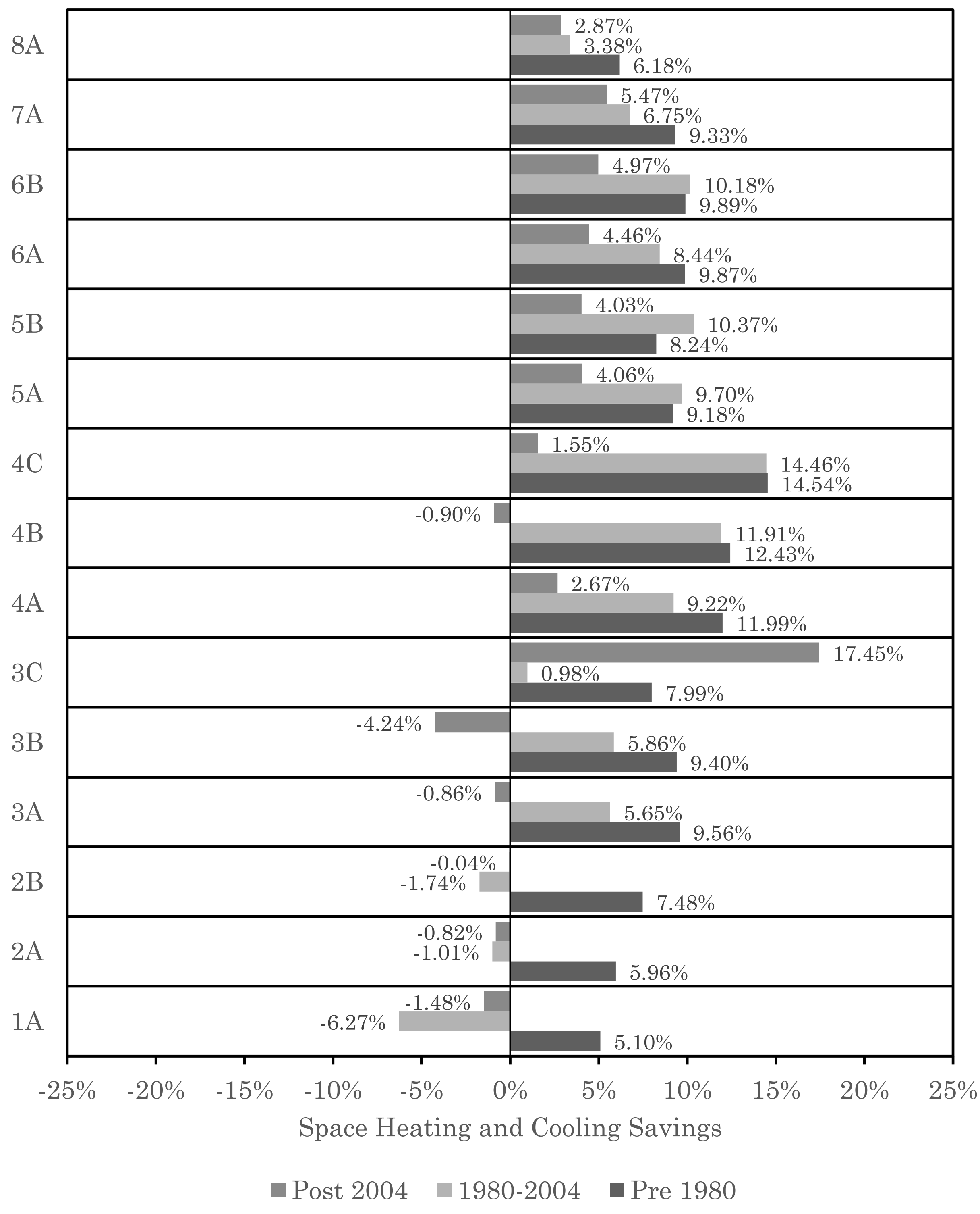

Figure 16. Percent savings of space heating and cooling energy for a Small Office for 15 climate zones across all building eras.

3.1.6. MIDRISE APARTMENT

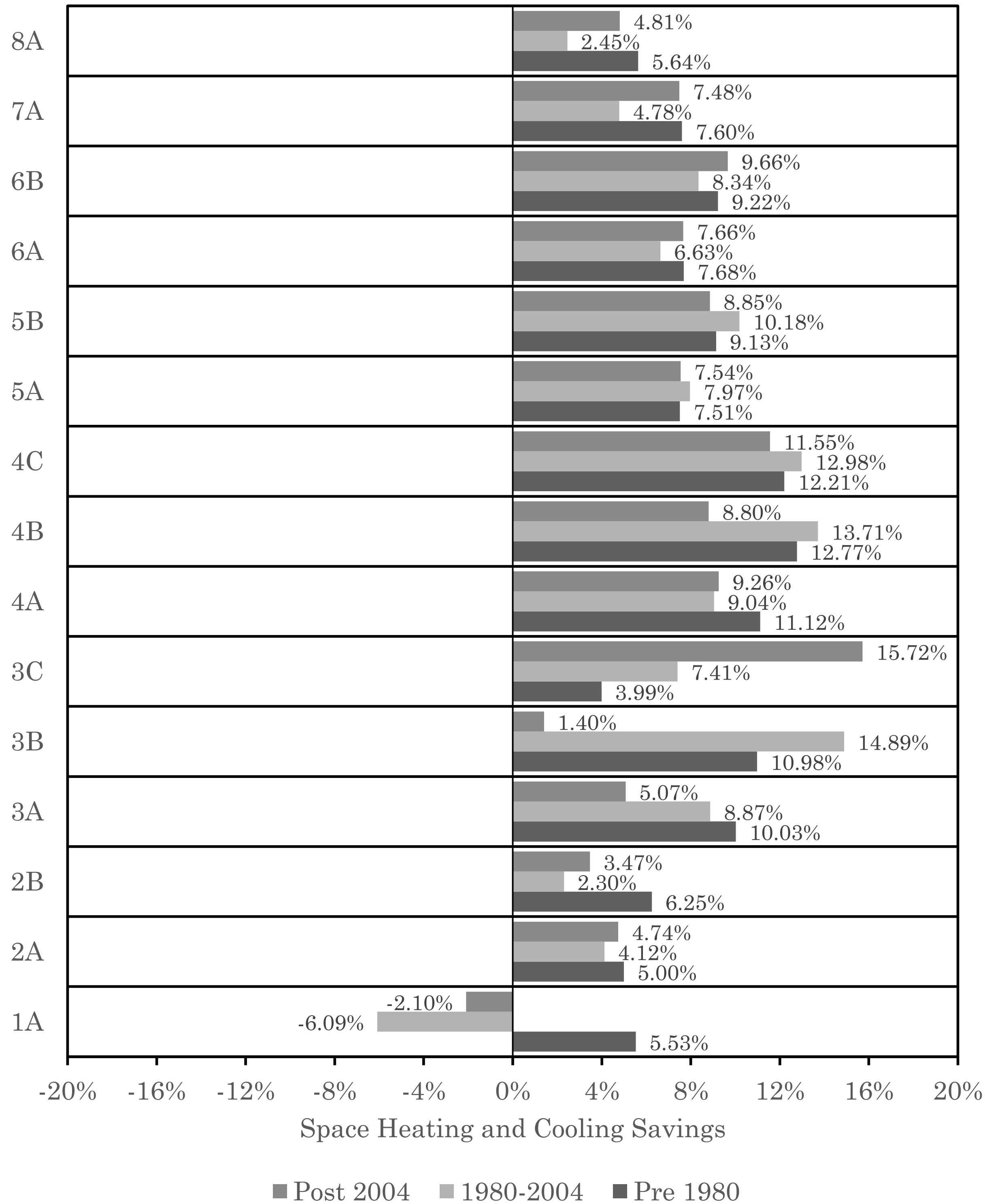

Figure 17. Percent savings of space heating and cooling energy for a Midrise Apartment for 15 climate zones across all building eras.

3.1.7. PRIMARY SCHOOL

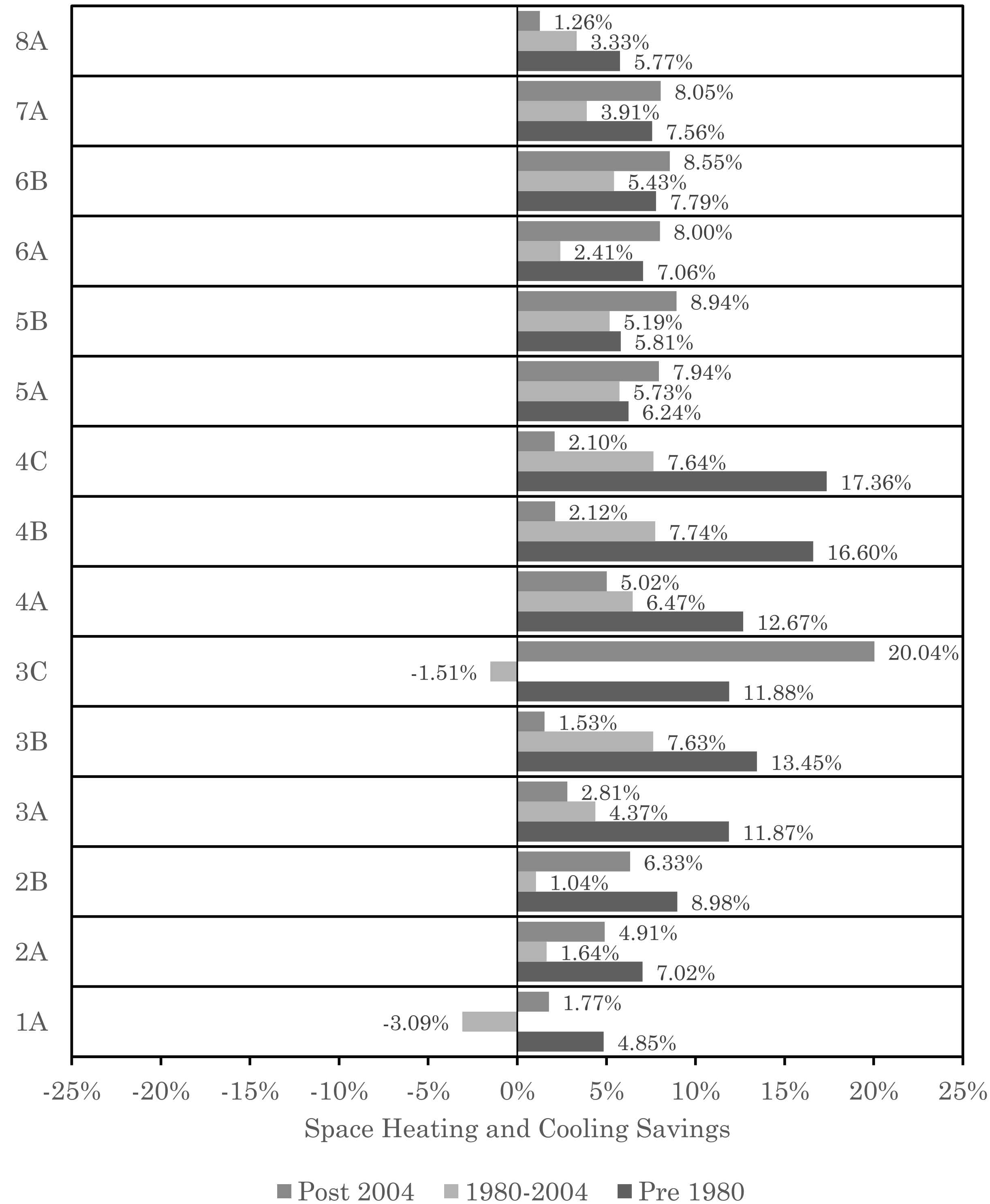

Figure 18. Percent savings of space heating and cooling energy for a Primary School for 15 climate zones across all building eras.

3.1.8. SECONDARY SCHOOL

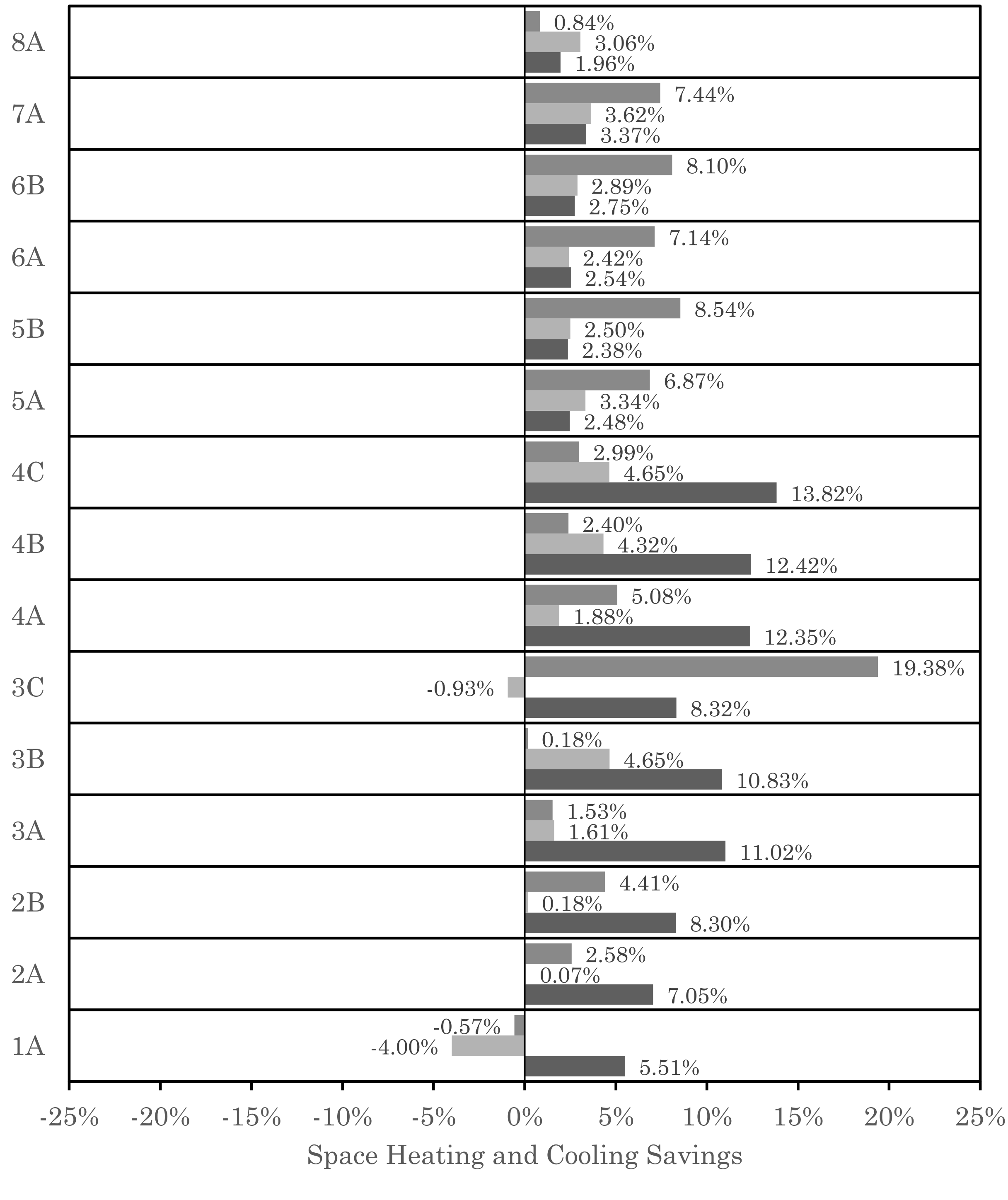

Figure 19. Percent savings of space heating and cooling energy for a Secondary School for 15 climate zones across all building eras.

3.1.9. RETAIL STANDALONE

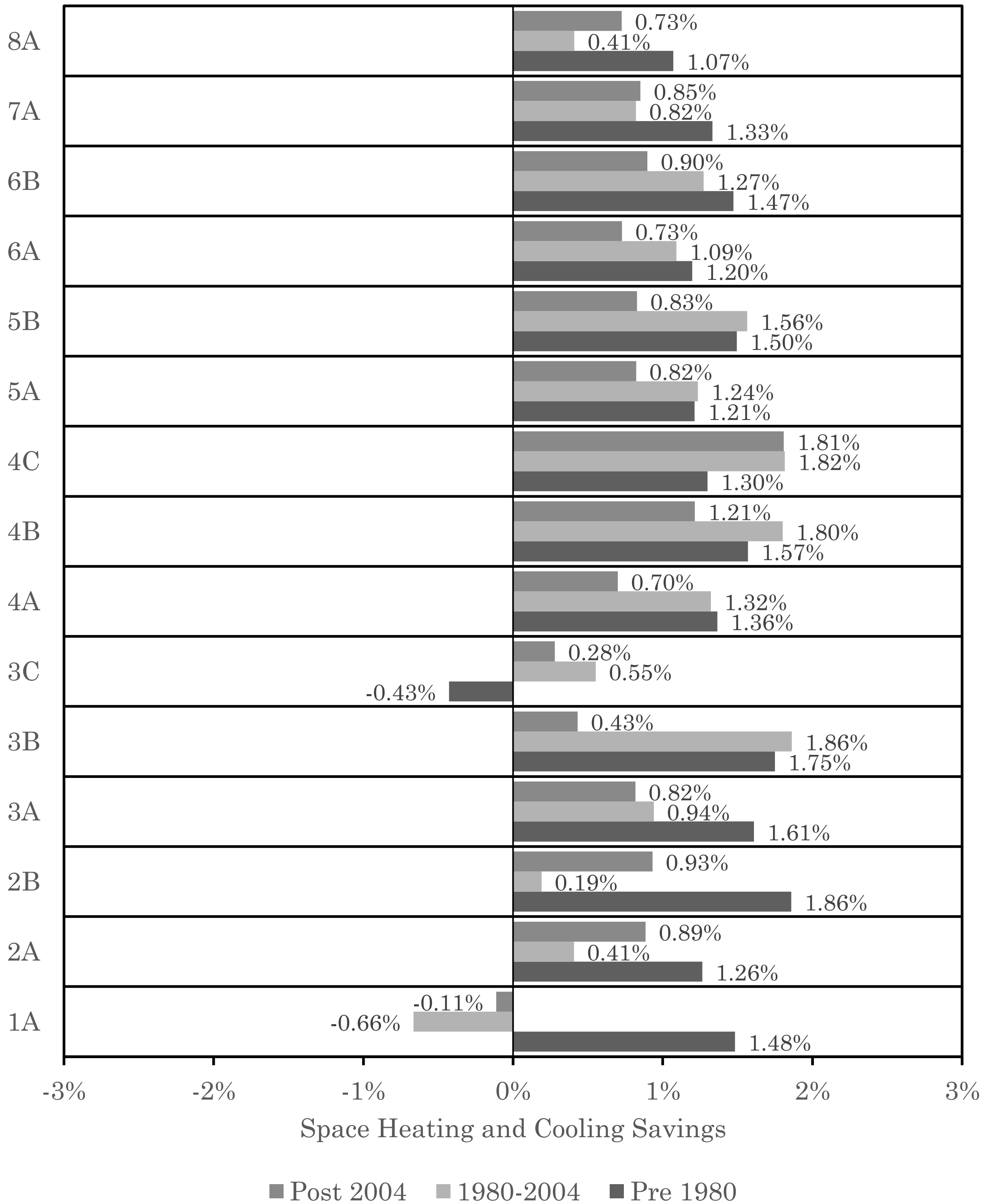

Figure 20. Percent savings of space heating and cooling energy for Standalone Retail for 15 climate zones across all building eras.

3.1.10. RETAIL STRIPMALL

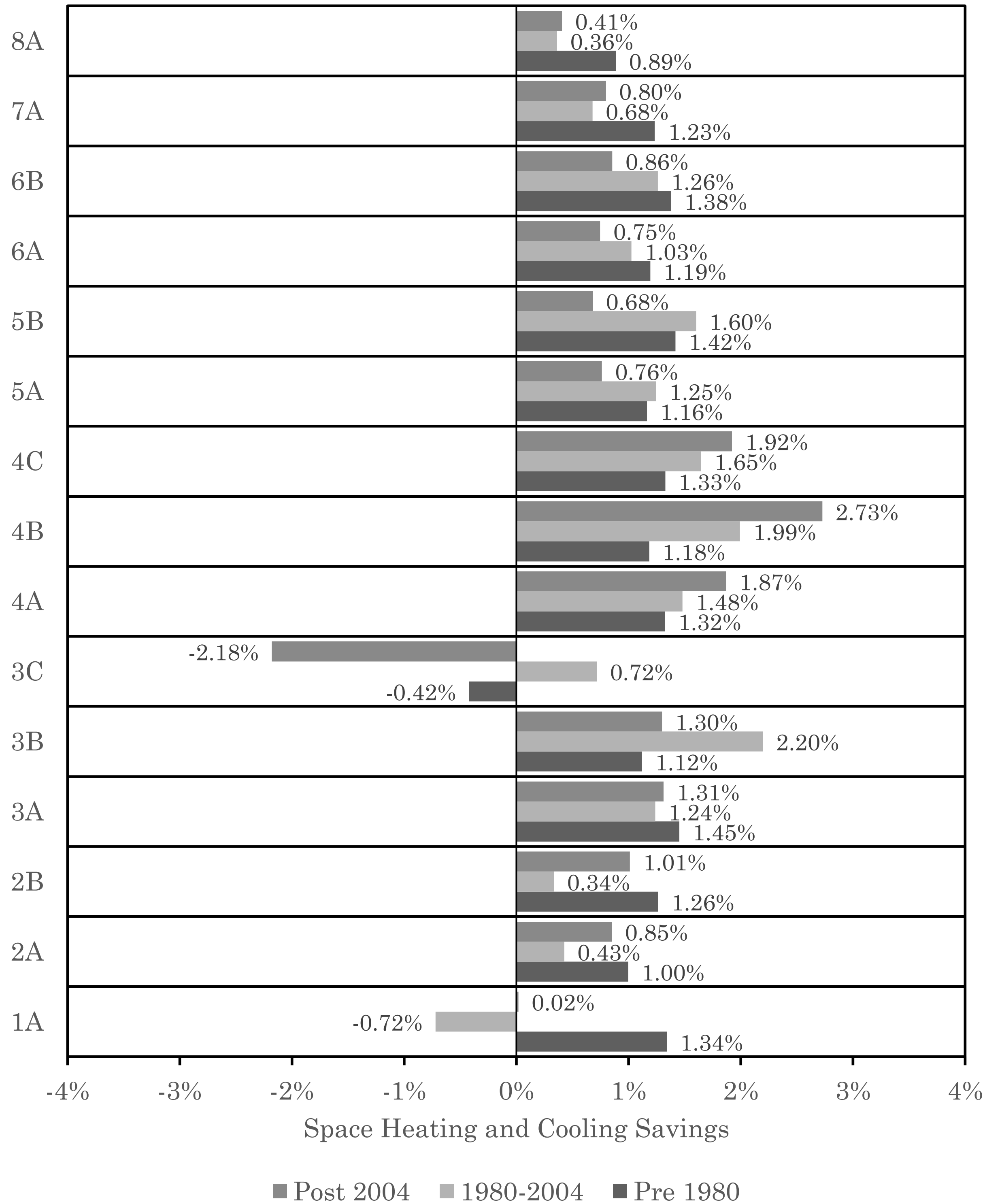

Figure 21. Percent savings of space heating and cooling energy for Stripmall Retail for 15 climate zones across all building eras.

3.1.11. WAREHOUSE

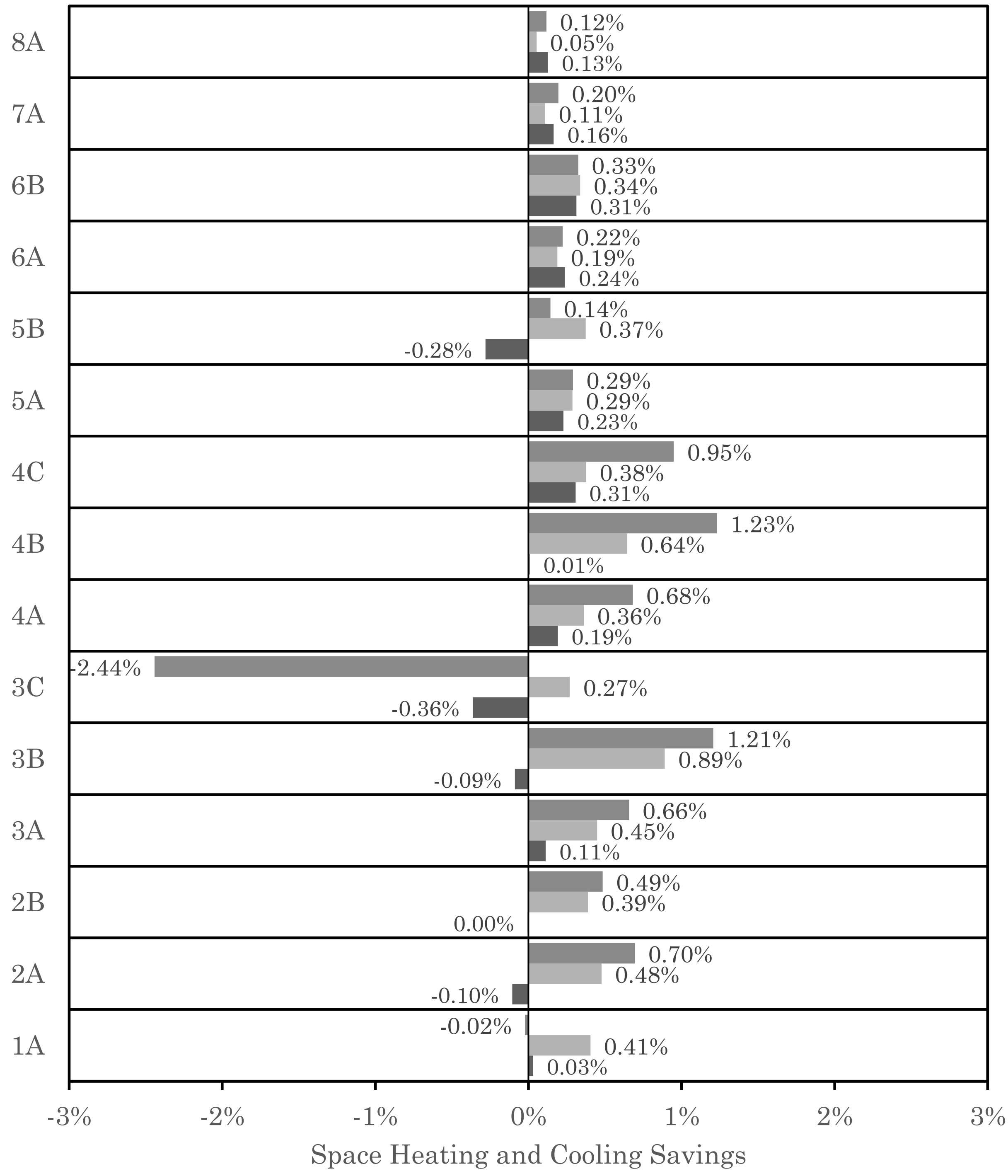

Figure 22. Percent savings of space heating and cooling energy for a Warehouse for 15 climate zones across all building eras.

3.2. OFFICE BUILDING INVESTIGATION

The Small, Medium, and Large Office buildings are the most similar of all the commercial reference buildings. Each building has identical operating schedules, efficiencies, and wall constructions. The variables that differentiate them are the building geometry and building program distribution. Figure 23 shows the various geometries of the office buildings. The Large Office is six stories, while the Medium Office is four stories, with the Small Office being a single story. Due to the difference in geometry, the wall constructions vary based on typical structural systems chosen. The Small and Large Office have the *mass* construction type, while the Medium Office are *steel frame*.

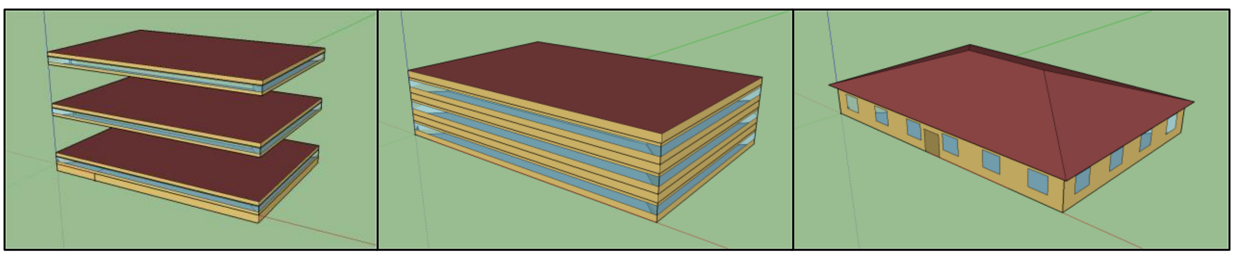

Figure 23. Large Office, Medium Office, and Small Office (left to right) building geometry. Note that buildings are not to scale to one another.

The office buildings are compared to one another within climate zone 4C. Figure 24 shows the space heating and cooling energy savings for TWC based window assembly retrofits. Large and Medium Offices see more savings in earlier building vintages as a result of high WWR and more thermally conductive window assemblies in reference buildings. Energy savings go down, although are still positive, in the later building vintages, yet the Small Office sees an increase in space conditioning savings for Post-2004 construction.

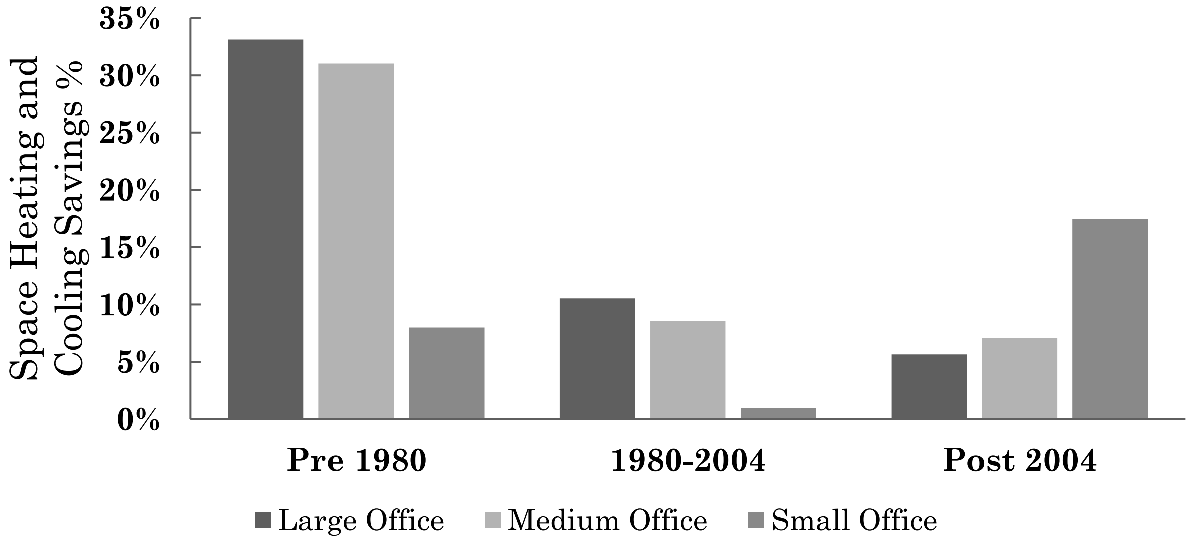

Figure 24. Comparison of different office buildings in climate zone 4C for all three building vintages.

3.3. MEDIUM OFFICE CASE STUDY BUILDING

The Medium Office building is used herein as a case study to understand how TWC-based windows affect the space heating and cooling on a monthly basis. Figure 25 describes the Pre-1980 monthly space condition comparison, while Figure 26 describes the Post-1980 comparison, and Figure 27 describes the Post-2004 comparison. In heating-dominated months, the buildings with TWC-based window assemblies perform better than the baseline windows across all building vintages. Yet, in the cooling months, the baseline building windows perform better than the TWC based windows. When the savings during the winter exceed increases in space cooling during the summer, annual energy savings are realized. For this particular building and climate zone in particular, the savings during the heating months were more than the cooling months, resulting in space annual space conditioning savings of 7.08%, 8.58%, and 31.02% for the Post-2004, Post-1980, and Pre-1980 buildings, respectively.

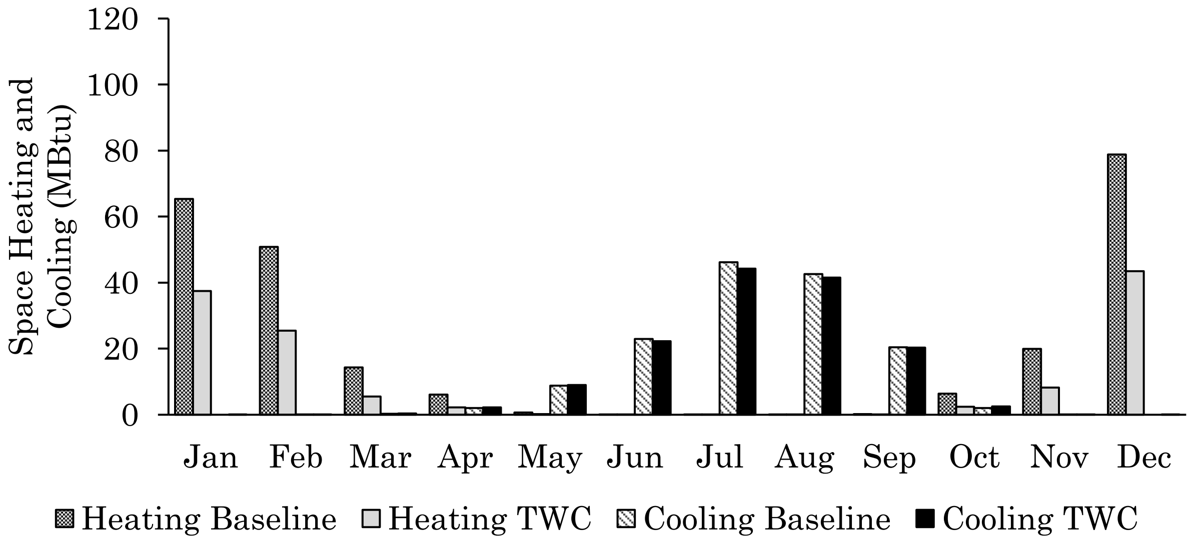

Figure 25. Monthly energy comparison for baseline and TWC retrofit space heating and cooling for the Pre-1980 Medium Office building in Climate 4C.

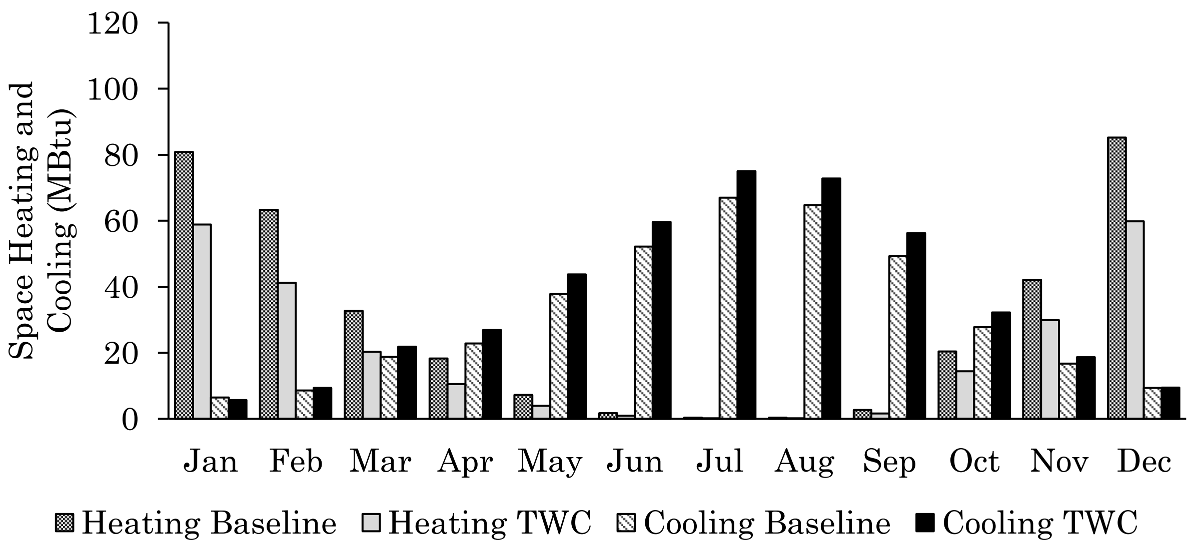

Figure 26. Monthly energy comparison for baseline and TWC retrofit space heating and cooling for the Post-1980 Medium Office building in Climate 4C.

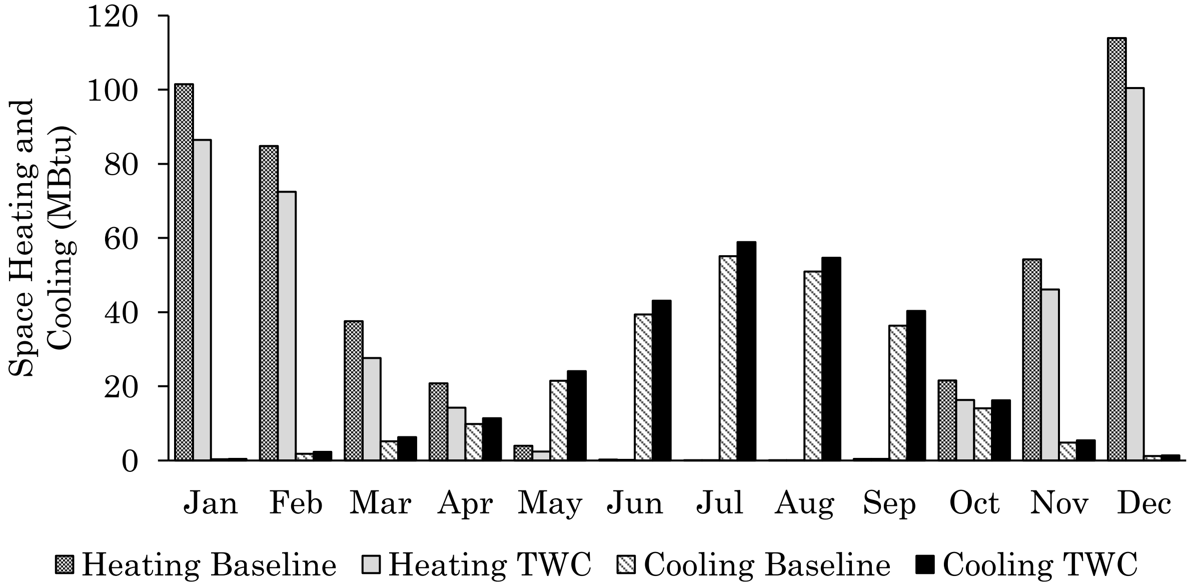

Figure 27. Monthly energy comparison for baseline and TWC retrofit space heating and cooling for the Post-2004 Medium Office building in Climate 4C.

3.4. WINDOW COST ANALYSIS

Products used in the building industry need to be economically viable. This section looks to give an order of magnitude cost estimate for TWCs manufactured at lab scale. The TWC fabrication method outlined in Section 1.4 is assumed to be a scalable manufacturing process for this cost estimate. Table 12 summarizes the materials, energy, and their unit costs for lab-scale TWC fabrication. It is assumed that 95% of the ethanol and acetone used for the solvent exchange process can be recovered. All quantities depend on the initial amount of wood, 5.5g for this example. A normalized cost of $0.82 per gram of initial wood is achieved. Figure 22 shows a cost breakdown by component contribution to the total cost. Of the materials needed, resin and sodium acetate make up 74% of the cost, while acetone accounts for 14%. The wood comprises very little of the total cost (3%).

Table 12. Materials and energy used to fabricate lab-scale TWCs.

Material or Energy	Quantity	Units	Unit Cost
Wood	5.5	g	$0.0042 /g
Sodium Acetate	12.3	g	$0.0275 /g
Acetic Acid	9.0	g	$0.0005 /g
Sodium Chlorite	15	g	$0.0001 /g
Water	3.5	L	$0.0032 /L
Ethanol	1.0	L	$0.5390 /L
Acetone	1.0	L	$2.2700 /L
Keep at 80°C for 12 hours	19.2	kwh	$0.0081 /kwh
Resin (PMMA)	27.5	mL	$0.1500 /g
Vacuum Oven	19.2	kwh	$0.1105 /kwh
36W Nail UV Lamp (2hrs)	0.072	kwh	$0.1105 /kwh

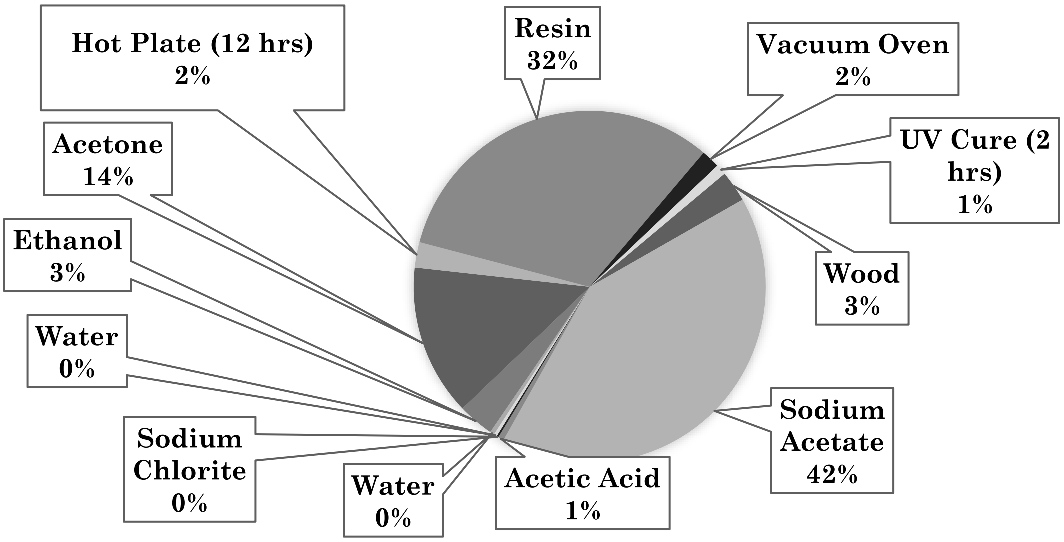

Figure 28. Breakdown by cost percentage of each component used in the fabrication process.

Compared to mass-produced silicon based glazing, TWC are an order of magnitude more expensive. The glass needed to create one square foot of a single-paned glass costs approximately \$3.00, while the cost of window using a single 14mm thick TWC pane is \$63.33 [19]. The payback period for the savings in energy usage is not on the timescale of the lifespan of the buildings. To make TWC based window retrofits feasible, the cost would need to be brought down to less than \$6.00 per square foot.

CHAPTER 4 CONCLUSIONS

4.1. SUMMARY

Alternative glazing systems can play an important role in reducing the energy consumption within buildings. Transparent Wood Composite based window systems offer improved thermal resistance over traditional glazing systems. Single-paned and double-paned window assemblies were created and implemented into an energy simulation within various commercial building types and climate zones. Buildings that saw the most savings in space conditioning were those with high WWR, while those with lower WWR did not see as much energy savings. For the Pre-1980 buildings, space conditioning energy consumption was reduced by 33.3% in the Large Office in climate zone 4C and 31.2% in climate zone 4B. TWC based window implementation in new construction reduced space conditioning by up to 24.6% in the Medium Office building located in climate zone 3C. Buildings with WWR decreased across buildings, fewer savings were seen with TWC based window implementations. Moderate climates are locations where savings due to TWC based window retrofits have the most potential for reducing building energy usage. Yet, not all building types and locations benefit from TWC based window retrofits. The Large and Small Hotels saw negative impacts due to TWC based windows. In addition, climates with high amounts of solar radiation, such as 5B, where the SHGC must be carefully controlled are not optimal locations for the TWC based windows used in this study.

Building geometry or compactness, WWR, and climate zone play an important role in the envelope performance. This study has shown that TWC based window systems tend to reduce a building's energy consumption in reference buildings, with up to 33% savings. Savings in commercial reference buildings are not representative of individual building designs. In-depth envelope and energy simulations are recommended for the implementation of any alternative glazing systems, including those that are TWC based.

4.2. FURTHER STEPS

The windows created in this study were simple single-paned and double-paned windows. Windows of various thicknesses and properties, still composed of TWCs, would allow for building designers to select appropriate glazing systems for a particular building. Optical properties of TWCs have not been studied to their full extent, especially in the context of view windows. A better understanding of TWCs' optical properties will give designers more flexibility in daylighting design. A balance between view windows and diffuse windows with increased thermal resistance can be achieved in building design to further decrease energy consumption. One metric not considered in the scope of this study is the reductions of lighting due to better daylighting. If effective daylighting strategies are implemented using TWC based fenestrations, reductions in total building energy use will increased. Yet, a daylighting study must be coupled with further energy simulations to account for the decrease in thermal loads due to light fixtures.

Polymers are inherently subjected to degradation as a result to Ultraviolet (UV) exposure. TWCs are composed of polymers and if used as windows will be exposed to high levels of UV light. Understanding the long-term durability of TWC based windows is essential for their use in the building industry.

The midrise apartment showed to be the most consistent energy savings across all building vintages and climate zones. Further investigation is needed into the application of TWC based windows into residential buildings. Due to operating schedules and WWR typical of residential buildings, it is expected that TWCs based window implementations lead to reductions in energy spent on space conditioning.

Wood is often presented as a sustainable material. Yet, TWCs are composed of both the cellulose-hemicellulose structure and resin (a polymer such as PMMA) which have different fabrication methods, and end of life assumptions. To fully understand how sustainable TWCs are, a lifecycle assessment incorporating all phases from extraction to use to end of life must be considered. This study only considered the effect TWCs have on operational energy. To gain a comprehensive view on how, as a material, TWCs can be sustainable, a full lifecycle assessment incorporating the embodied impacts is needed.

Windows are an important aspect of the architectural experience of a building. Replacing silicon-based glazing, which has low haze, with TWC based windows with high haze would give very little views to the exterior. As such, the architectural experience would not be the same between the two glazing systems. Further development of TWCs to reduce the haze will make TWC based glazing more competitive to traditional silicon-based glazing systems.

Many of the properties of TWCs are unknown and not the best for certain conditions. For example, due to TWCs having a relatively high SHGC, climate zones that have high amounts of solar irradiance (such as 5B), the heating savings in the winter due to both the higher SGHC and lower U-value do not overcome the increased cooling loads during the summer time. If the SHGC of TWC based windows could be variable, like that of typical glass based windows, designers can have more control over the performance of the building envelope.

4.3. CONCLUDING STATEMENT

While the development of TWCs are still at lab-scale, their potential for operational energy savings in the building industry proved to be promising. The TWC based window assemblies investigated in this study are effective in reducing the energy spent on space conditioning across many commercial building types and climate zones. Further study into the daylighting applications of TWC based fenestrations will provide a better understanding of the potential TWCs have in the built environment.

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